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A Comparative Analysis of Internal and External Solutions to Provide Air Combat Maneuvering Instrumentation Functionality

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Abstract

Air Combat Command (ACC) relies on Air Combat Maneuvering Instrumentation (ACMI) systems for air-to-air combat training and large force employment flight debrief. Although extremely effective training enhancements, these systems are enormously expensive and typically require flight over restricted airspace ranges. These factors have prevented fleetwide implementation of ACMI training on a daily basis. Basic ACMI systems determine aircraft position and performance data and transmit the data to ground-based monitoring stations for recording, display, and debrief. Early jet fighter aircraft required special external components, or "pods," to calculate and transmit the data to custom-built computerized debrief facilities. Modern aircraft do not retain this limitation, and low-cost personal computers now offer computational and graphics display capability sufficient for ACMI debrief. Current avionics systems calculate all the necessary data and report the required parameters on the aircraft avionics system bus. Monitoring and recording this onboard data will reduce the requirement for special ranges, eliminate pod requirements, and allow debrief and presentation on conventional computer equipment typically available in fighter squadrons. Internal data also offers avionics parameters that are not available to pod-based systems. This data represents an enormous untapped resource for flight debrief. Perhaps the greatest potential contribution offered by internal systems involves combat mission debrief capability. Because external pods occupy weapons stations, it is extremely unlikely that crews would ever carry these components into combat. Internal components are the only alternative that can provide ACMI features for a combat mission debrief. Additionally, internal components preserve the aerodynamic and radar signature characteristics of the aircraft, a feature essential for stealth aircraft employment.

This new ACMI concept would reduce the requirement for external pods and other support equipment and provide basic ACMI functionality for every mission with potentially significant cost savings compared to current and planned pod-based implementations. The proposed alternative can also serve as an essential supplement to large force training exercises, as these missions will likely continue to rely on external pods. This proposal for an internal solution trades the unique features required in large package exercises for convenience, ease-of-use, and daily availability of basic ACMI functionality without degrading the value of realistic combat training. Providing basic ACMI functionality on daily missions offers significant synergies when combined with occasional full-scale exercises.

ACC is currently developing a new ACMI pod and advanced training system. The system under consideration, known as the Joint Tactical Combat Training System (JTCTS) combines Global Positioning System technology with ACMI equipment and provides a wide range of new features. Proposed capabilities include electronic warfare training, "no drop" munitions delivery training, and the ability to link simulators and virtual training systems with live-fly missions. For this application, a pod-based system may be the best solution in the near term. However, basic ACMI features can be provided for all modern aircraft

using internal components. Developing this capability will allow enhanced training in any airspace while eliminating the costs (fiscal and performance) of a pod-based system, while providing valuable experience in designing internal alternatives required by future aircraft.

The decision to acquire or lease another pod-based system limits the potential to investigate the benefits and risks of developing internal capability. Future aircraft, including the F-22 Stealth fighter and the proposed Joint Strike Fighter will require internally based systems to maintain stealth characteristics. Failure to develop alternatives to pod-based systems ahead of time will inevitably increase the cost and risk of providing ACMI functionality for future aircraft. This research proposes alternatives that rely on avionics components currently installed on modern and future aircraft. Integrating the capabilities of existing hardware can offer insights for the development of a new, full-featured internal system.

This study presents a summary of the development of the current and proposed family of ACMI systems and the capabilities each system provides. The Kadena Interim Training System provides a suitable case study to compare requirements of current ACMI features to the capabilities available using internal components.

Properly implemented, the proposed alternatives offer the potential to save millions of dollars in operating costs and allow ACMI training on every mission independent of ground-based equipment and external stores. Internal components can provide cost-effective basic ACMI functionality with the potential to offer capabilities approaching the next-generation system, as well as providing new features never before available on pod-based systems. Internal systems can be installed long before the next-generation system will be operational and will provide a routine availability that will not be offered by JTCTS. Leveraging the capability of internal components will further increase combat mission training effectiveness today, as well as reduce the technical and fiscal risk of developing future systems.

About the Author

Maj Michael T. Panarisi was commissioned by the United States Air Force Academy (USAFA), Colorado Springs, Colorado, in 1986. Graduating from Specialized Undergraduate Navigator Training, he went on to fly the F-111F as an instructor weapons systems officer and functional check flight crew member at RAF Lakenheath, United Kingdom. During this assignment, he flew numerous combat and combat support missions in Operations Desert Shield, Desert Storm, and Provide Comfort. He was subsequently selected to transition into the F-15E, where he served an additional tour at RAF Lakenheath as an instructor weapons systems officer and functional check flight crew member. During this assignment he flew numerous combat and combat support missions in operations Deny Flight, Deliberate Force, and Northern Watch. Following these assignments, he was selected to attend the USAF Test Pilot School at Edwards Air Force Base, California. Upon graduation, he was assigned to the 445th Flight Test Squadron and flew flight test and avionics integration missions in the US and foreign models of the F-15. Major Panarisi is a senior navigator with more than 1,500 flying hours. Major Panarisi earned a bachelor of science degree in engineering mechanics from USAFA and a master's of aeronautics degree from Embry–Riddle Aeronautical University. In August 2000, Major Panarisi was assigned to the 32d Air Operations Squadron, Ramstein Air Base, Germany.

Preface

Success in the modern air-to-air combat arena hinges on effective and realistic peacetime training. Solving the air-to-air training problem has consumed enormous amounts of time and money since the development of modern fighter aircraft. Over the years, flyers have developed numerous methods of enhancing training sortie effectiveness. In the past 20 years, the most promising effort involves the ability to accurately recreate mission events in a manner that allows a detailed discussion and evaluation during the postflight debrief. What initially began as a pilot struggling to physically record essential information during the flight has developed into a family of sophisticated electronic systems that transmit and record the data for "big screen" presentation and review. Initially referred to as Air Combat Maneuvering Instrumentation (ACMI), this system has proven itself as the "gold standard" of training mission enhancements. Unfortunately, even the most recent attempts to improve on the original ACMI concept have retained many of the early system limitations. The most significant drawback involves reliance on externally mounted pods. Reliance on external components has relegated ACMI training to occasional use and prohibits ACMI features on combat mission debriefs. Reversing this trend will greatly reduce the cost and complexity of ACMI systems, provide fleetwide routine access, and increase the data available for debrief, as well as preserve stealth characteristics of future aircraft.

Recent advances in modern aircraft avionics now allow internal components to perform the functions previously requiring external pods. ACMI missions require accurate aircraft attitude and position data. Calculating and transmitting this data were the primary functions of the original ACMI pods. Current and future generations of fighter aircraft include avionics that accurately measure these parameters. Modern aircraft also carry other onboard systems capable of transmitting the data between participating aircraft. Special instrumentation packages on developmental test and evaluation aircraft also perform these functions without requiring external components. Leveraging these internal components highlights the feasibility of an internal ACMI data collection and recording system. Personal computers now provide computational and graphics display capability sufficient for ACMI debrief, reducing the requirement for custom-built graphics processing and display hardware. With these facts in mind, it seems only logical to pursue "podless" alternatives to provide ACMI functionality. This research effort proposes such alternatives. Continued research and implementation of optimized podless designs will further improve combat mission training for current and future aircraft.

The alternatives proposed in this study are not intended to completely replace existing or planned ACMI systems, or what are now being referred to as air combat training systems. Modern systems create vastly complex "virtual combat zones" for high-fidelity, full-scale joint exercises. For these implementations, a pod-based system offers significant advantages in the near term.

What pod-based systems cannot offer is a fleetwide, continuously available training enhancement. Internal solutions meet this requirement with only minor aircraft modifications and for potentially extremely low cost per mission. The alternatives in this study can bring the renowned benefits of basic ACMI functionality to every mission.

Acknowledgments

This research could not have been accomplished without the unwavering and tireless efforts of my advisor, Lt Col David Couliette, and reader, Lt Col Forrest E. Morgan. I will be forever indebted to them for their constant encouragement and endless assistance on this project. Additionally, I would like to thank the instrumentation and avionics engineers of the 445th Combined Test Squadron at Edwards Air Force Base, California, for their expert analysis and continuous technical support. Specifically, Mr. James Barduniotis of Boeing and Mr. Michael Golackson, GS-15, provided countless hours of support and advice. Without their help, this report would never have been completed.

Chapter 1

Background

To lead untrained men into battle is to lead them to their death.

—Mao Tse-tung

The nature of peacetime training missions requires accurate and detailed mission debriefs. During these sessions, the aircrews evaluate performance, identify mistakes, and reinforce the lessons learned throughout the flight. Accurately reconstructing the mission events is perhaps the most challenging aspect of the mission debrief.

Debrief Techniques

Modern fighter aircraft capitalize on maneuverability, and success or failure in weapons employment hinges on the pilot's ability to position the aircraft properly in three dimensions. In order to accurately assess pilot performance, instructors and flight leaders must be able to display graphically the position and attitude of the aircraft at various points throughout the mission. To accomplish this task, aircrews have relied on numerous techniques with varying degrees of success.

Manual Methods

Manual methods rely on the aircrews' ability to recreate the mission events by sketching snapshots of the aircraft on a suitable display surface, such as a whiteboard. The crew develops these sketches by referencing notes, stick figures, and comments written during the flight. This technique requires the aircrew to physically record these items, often during highly dynamic maneuvers (fig. 1).

To reduce the workload during the flight, many crew members have developed templates that simplify the recording of standardized parameters such as the event times, headings, and altitudes (fig. 2). These templates also provide an organized method for recording basic sketches of maneuvers as they occur. From these templates, the aircrew can reproduce the flight events on a whiteboard.

As the event begins, the aircrew enters the appropriate data and begins to annotate the template. As the maneuver progresses, the aircrew sketches the flight activity using standardized notation elements. If the template is used for depicting a turning engagement, each template typically represents between 90 and 360 degrees of turn depending on the level of activity within each turn. As the maneuver progresses, the aircrew uses additional templates as necessary to complete the record of the

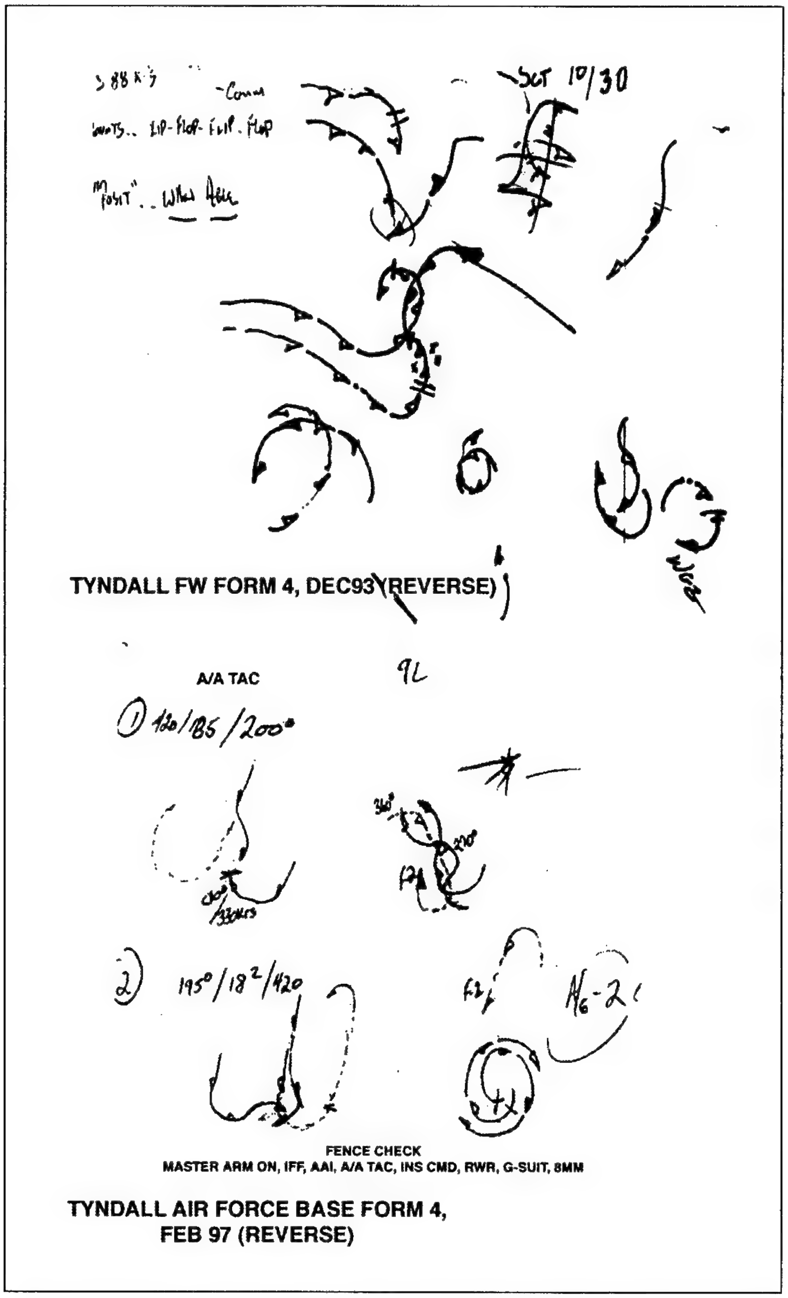


Figure 1. Samples of Hand-Recorded Flight Maneuvers

event. From these sketches, the aircrew will attempt to recreate the maneuver during the debrief (fig. 3).

Although this technique is by far the most widely used method, it presents serious limitations. Perhaps the greatest limitation involves the risks inherent in diverting aircrew attention away from critical tasks while composing the sketches and recording the necessary information. The aircrew

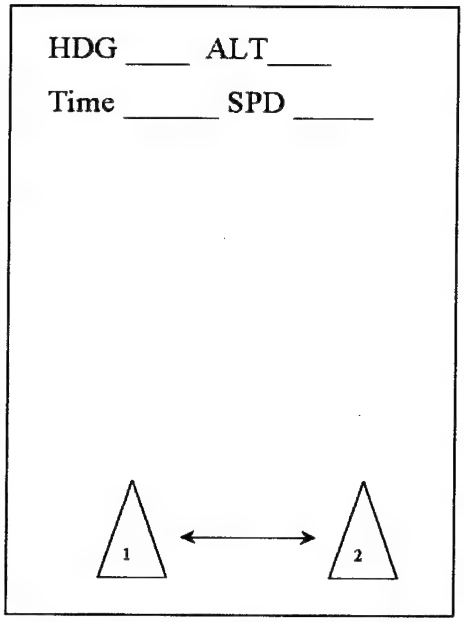


Figure 2. Sample Debrief Template

must decide when changes in the data are pertinent, and missing important events can lead to inaccurate reproductions during the debrief. Certain aspects of the flight events—including weapons employment, airspeed, and maneuver capability—may include classified information, requiring the aircrew to treat the templates or other notes as classified material. This requirement increases the risk of compromising the aircraft performance data in the event the flight notes are lost or misplaced. These methods are also subject to the perceptions of the person recording the data. Highly dynamic maneuvers can create false impressions of attitude and position, again resulting in inaccurate debrief reconstructions. These false impressions are also a result of the three-dimensional nature of aircraft maneuvers.

Most aircraft maneuvers involve three-dimensional position changes. When the pilot alters aircraft attitude quickly, the aircrew often misperceives the actual aircraft response. It is also difficult to transcribe these maneuvers onto a two-dimensional surface. Consequently, the aircrew must rely on shorthand abbreviations and perceptions of the actual aircraft

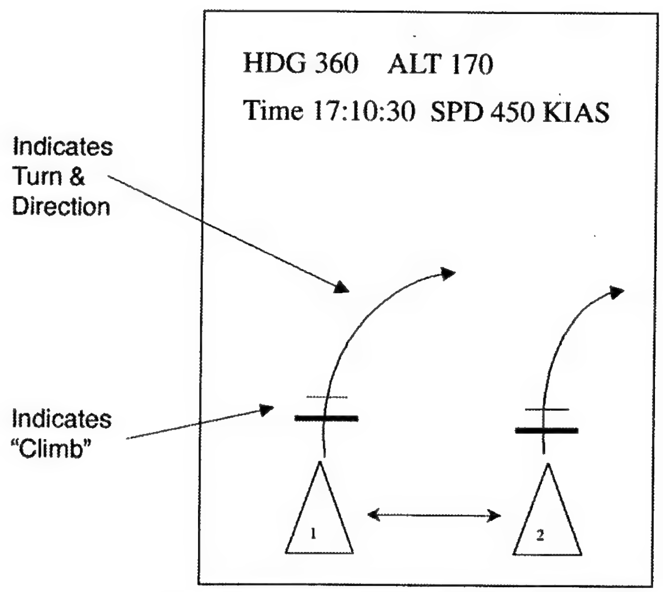


Figure 3. Sample Template with Flight Data Annotations

performance. These estimates and potential misperceptions compound the possibilities of misrepresenting the aircraft maneuver during debrief. Misrepresentations can lead to erroneous conclusions about aircrew performance and maneuver effectiveness.

Audio Recording Systems

In an effort to increase the accuracy of the sketches developed during the flight, aircrews have used in-flight audio recordings of cockpit and radio transmissions. These recordings provide a narration that can be used to highlight or reinforce various aspects of the flight. These recordings also provide a history of interflight communications, useful for assessing aircrew communication procedures. During highly dynamic maneuvers, the aircrew can talk into the tape instead of attempting to draw items onto the template. For example, the pilot may state "in a right-hand turn, descending, passing through 17,000, 5 Gs." This technique reduces workload and allows the aircrew to focus more attention on critical tasks.

Combined with the information annotated on the sketches, the aircrew can create a more detailed picture of the flight events. However, this technique also poses several limitations. If the aircrew relied solely on narrations provided by audiotape, equipment failure would negate the training value of the mission. The equipment also poses potential risks in the cockpit. Unless the recorders are built into the aircraft avionics, the additional cables and hardware could potentially become dislodged and pose foreign object damage hazards during the flight. The narrations are also subject to misperceptions similar to those associated with handwritten notes. If the aircrew wishes to compare the recordings of several different aircraft, then synchronizing the narrations becomes a difficult, time-consuming task. The recordings may inadvertently become classified if the crew accidentally comments on sensitive aspects of the aircraft or maneuvers.

Aircraft Videotape Recorders

Most modern fighters now include aircraft videotape recorders (AVTR) that provide permanent recordings of selected aircraft avionics. Initially, the recordings focused on the aircraft gun sight or Head Up Display (HUD) and provided a recording of the pilot's forward view and associated aircraft performance parameters. These recordings are extremely useful in reconstructing the flight events, as the pilot's forward view offers the most accurate depiction of the aircraft position and movement during maneuvers. These recordings also allow an assessment of weapons employment if the target aircraft passes directly in front of the pilot.

More sophisticated AVTR systems time-share, or multiplex the recording function among several avionics components. These may include radars, weapons displays, radar warning receivers, or infrared seekers. Combined with cockpit and radio transmission audio, these sophisticated recordings

provide a highly detailed account of the flight. However, even this technique poses limitations. Due to the nature of modern avionics, these tapes are nearly always classified and must be treated as such. Many also require specialized playback equipment to interpret multiplexed recordings. These recordings share the synchronization and equipment failure risks of the earlier audio recording techniques, and reviewing the recordings of each maneuver becomes very time-consuming during the debrief. These tapes do not provide a depiction of the aircraft's actual flight path, only a record of the aircraft attitude. For highly dynamic maneuvers, the aircraft attitude can be completely independent of the aircraft flight path.

Conducting the Debrief

The primary purpose of the debrief is to recreate important aspects of the mission as accurately as possible. This procedure allows the aircrew to identify mistakes and evaluate performance. Typically, the flight lead or instructor is responsible for conducting the debrief. The aircrew will collect any available data on the sequence of events and attempt to recreate the mission by drawing representations of the maneuvers on a suitable display surface, such as a whiteboard. Colored pens allow the illustrator to differentiate between flight members and flight paths. In order to create a three-dimensional depiction on a two-dimensional surface, the aircrew uses special annotations and may switch between top- and side-view drawings.

The accuracy of these drawings is highly dependent on the data recorded during the flight and the artistic skill of the crew member constructing the illustrations. A combination of written comments, audiotape and videotape recordings, and a review of other flight members' data offers the best opportunity to recreate the mission accurately. However, the requirement to compile the various sources of data becomes extremely time-consuming and often causes debriefs to last many times longer than the actual flight.

Limitations of Manual Methods

Although aircrews have become proficient at manually reconstructing the mission events, these methods still pose serious limitations. For relatively benign maneuvers, manual methods can provide the data required to accurately recreate the sequence of events and the relative position of participating aircraft. As maneuvers become more dynamic, a simple order of events does not satisfy the requirement to assess aircrew performance. The data requirements expand exponentially as the flight complexity increases, and the number of events rises as well.

The debriefer must judge each maneuver for timeliness, execution, and tactical appropriateness. Manual methods do not provide sufficient data for a clear, error-free debrief in complex, highly dynamic air-to-air engagements. The data required includes aircraft position and performance

information necessary to evaluate aircraft energy, range, aspect angle, and turn performance. These parameters form the complete picture of the aircraft and aircrew performance throughout the tactical engagement. Manual methods also lack the capability to depict aircraft maneuvers adequately. This limitation involves the difficulty in representing three-dimensional maneuvers on two-dimensional media.

Energy Assessment

Air-to-air combat maneuvering requires the pilot to properly manage the amount of energy expended during each maneuver. The combination of potential and kinetic energy allows the pilot to convert energy into maneuvers. Throughout the maneuver, the pilot must regulate thrust, altitude, airspeed, attitude, and "G."[1] The magnitude and direction of the aircraft motion forms the aircraft "lift vector." Controlling this lift vector is the primary method of changing the aircraft flight path. Every change in the aircraft flight path forces the pilot to expend a portion of a limited supply of energy. Some maneuvers require only an exchange between potential and kinetic energy. For example, the pilot may elect to descend to gain airspeed, trading potential energy for kinetic energy. However, most maneuvers require the pilot to choose the appropriate time to spend the right amount of aircraft energy. Most of this energy is consumed by aerodynamic drag.

Aerodynamic drag on the aircraft constantly drains the maneuver energy available to the pilot. Most maneuvers increase drag on the aircraft; however, some maneuvers actually reduce drag. The skilled pilot increases or decreases drag at the appropriate times to preserve energy and maneuver capability. If the pilot expends too much energy during maneuvers, the aircraft airspeed or altitude will decrease, reducing maneuver capability. In the extreme case, the pilot could literally fly the aircraft out of airspeed and altitude and impact the ground. Because the energy level and consequent maneuver potential of the aircraft is a combination of several factors, it is essential that the debriefer determine the relationship between these factors in assessing energy level. This assessment is a critical component of the debrief. Manual methods offer a poor technique for assessing energy levels and potential maneuver capability.

Position Assessment

Determining the position of participating aircraft is another critical debrief component. The position of opposing aircraft must be determined in order to assess maneuver effectiveness and weapons employment. Both the position of the opposing aircraft and the execution of maneuvers involve three-dimensional problems that must be evaluated. It is also important to review the formation position of wingmen throughout the flight. To describe the relationship between the aircraft, aircrews use a combination of range and angle parameters. The magnitude and direction

of the aircraft velocity forms the aircraft flight path vector, and control of this vector is the critical task during an engagement. The relationship between opposing aircraft positions and vectors are described in terms of range, aspect ratio, angle off, and heading crossing angle. Accurately determining and reviewing the complex series of position changes throughout the flight is critical in understanding the effectiveness of the various maneuvers performed.

Range Determination

The distance, or range between the engaged aircraft is another essential debrief parameter. The range between two aircraft is a function of horizontal and vertical distance. This distance determines the amount of "turning room" available to each aircraft. In a three-dimensional perspective, "slant range" is the true distance between the two aircraft. The horizontal range is often referred to as "ground range," and the vertical range is known as the altitude "Delta" (fig. 4).

Although primarily a function of weapons employment, the distance between the aircraft also determines the appropriateness and timeliness of maneuvers. Accurately determining the distance between aircraft allows the debriefer to assess the effectiveness of weapons employment and the maneuvers executed during the flight.

Successful weapons employment requires the pilot to position the aircraft and fire the weapon within specified ranges. Most weapons, such as missiles or bullets, have prescribed minimum and maximum employment ranges or "envelopes." Attempting to employ the weapons outside of these

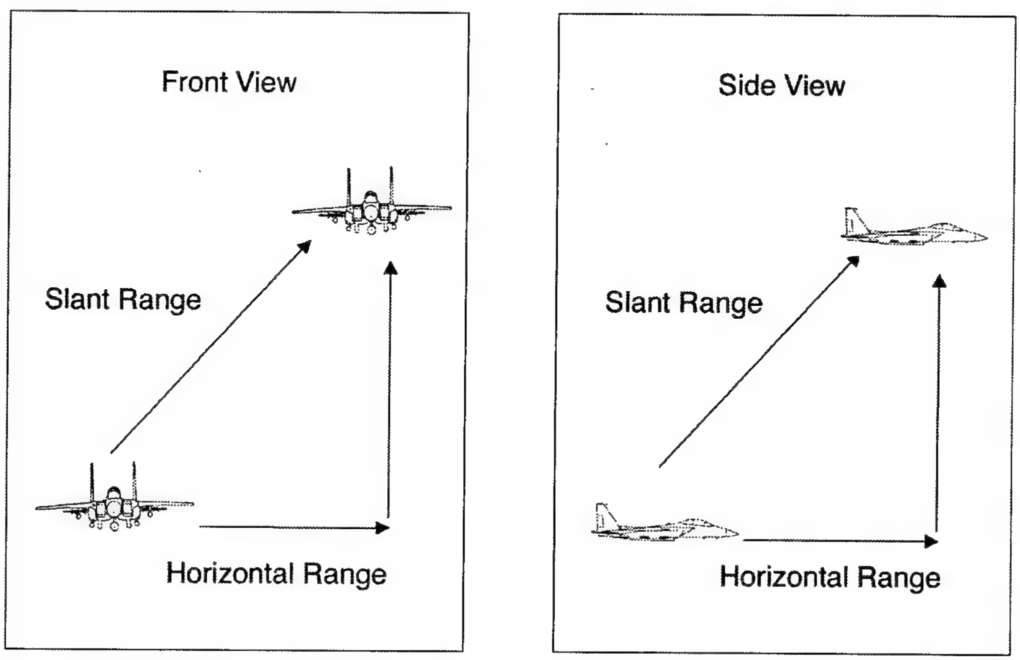


Figure 4. Depiction of Range Parameters

envelopes greatly reduces weapon effectiveness and probability of kill (PK). During the debrief, it is essential that the aircrews determine the point at which weapons were employed and the distance and angles between the aircraft at the moment of launch.

Using manual methods, the aircrews are severely limited in their ability to accurately determine the distances between aircraft. The primary method in modern aircraft requires crews to illuminate the target aircraft with onboard radar. This device will provide various degrees of accuracy dependent upon the mode used and the position of the target aircraft. Currently, radars only provide distance information on aircraft in a relatively small cone in front of the aircraft, with no information on aircraft to the side or behind. Alternatively, most aircraft are equipped with tactical area navigation (TACAN) equipment; and when used in the air-to-air mode, these devices provide continuous displays of the distance between the aircraft. However, these devices only provide slant-range measurements and do not display the relationship between horizontal, vertical, and cross-range parameters. TACANs are also susceptible to interference from nonparticipating aircraft.

TACANs determine range with a transponder technique between each component. For ground navigation, the crew tunes the receiver to the channel assigned to the desired ground location. The TACAN displays in the cockpit show the range and bearing to this ground station. TACANs can also display distance information between aircraft in the air-to-air mode. In this mode, the crew can designate a flight member (usually the flight lead) as a surrogate ground station. This aircraft serves as the "mother ship." The other flight members can determine the distance to this aircraft by selecting a TACAN channel number that is 63 units higher than the channel in the mother ship (if the mother ship is tuned to channel 3, the "daughter ships" tune to channel 66). Although very useful, this technique can only provide distance information against a single mother ship aircraft. No distance information is available between the "siblings." If another flight (even a flight up to 50 miles away) inadvertently chooses the same channel pair, the readings between the aircraft will become erratic and unreliable. Barring the availability of these avionics components, the aircrew can estimate the distance using visual cues; but this method is only a very rough estimate, often with errors in thousands of feet.

Beyond weapons employment, the range between aircraft is also a critical parameter for determining the appropriateness and timeliness of maneuvers. Executing a maneuver either too close or too far away from the opponent usually negates the effectiveness of the maneuver, wastes precious energy, and may even force the aircraft into a seriously dangerous position. By determining the distance between aircraft when maneuvers are executed, the aircrew can assess the performance of these maneuvers during the debrief.

Aspect Angle Determination

Aspect angle is another critical parameter that must be determined during the debrief. Aspect angle is the primary parameter the pilot must control for successful weapons employment and is a primary factor in determining weapons employment envelopes. By definition, aspect angle is a number of degrees measured from the tail of the target aircraft to the position of the maneuvering aircraft (fig. 5). It is important to understand that aspect angle is independent of maneuvering aircraft heading and only a function of position, while the target aircraft heading is a critical component of aspect angle. The pilot must choose the appropriate maneuvers that increase, decrease, or maintain aspect angle while fighting for position and range. Manual methods provide only limited data to determine this crucial debrief parameter. If the maneuvering aircraft has the target aircraft "locked" on the radar, the radar can accurately display the aspect angle. When the target aircraft is not locked, the pilot must estimate aspect angle—typically relying on visual cues. Misperceiving the aspect

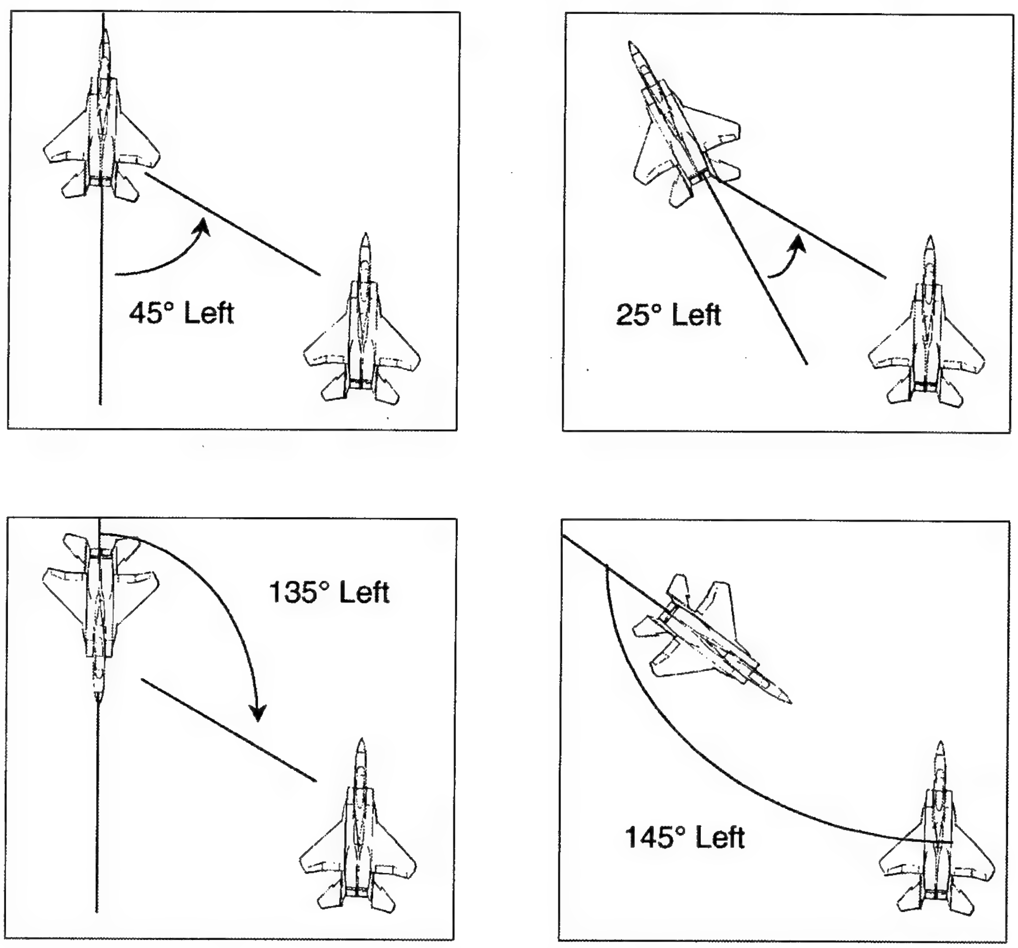


Figure 5. Depiction of Various Aspect Angles

angle can result in poor maneuver and weapons employment decisions. Without radar information, manual methods do not provide sufficient means of debriefing aspect angle measurements.

Assessment of Turn Performance

Maneuver effectiveness is a function of the aircraft turn performance. If the pilot elects to attempt a maneuver that is beyond the turn capability of the aircraft, the maneuver can potentially result in a disadvantageous tactical position or deplete valuable energy. By combining a perception of position, range, and aspect angle, the pilot must decide if a particular maneuver is within the capability of the aircraft and predict the relationship between these variables at the end of the maneuver. The end result of the maneuver is a function of the aircraft turn rate and turn radius.

Aircraft turn rate is measured in degrees per second and describes how quickly the aircraft can change direction. The aircraft turn radius is a measurement of the amount of combined horizontal and vertical distance the aircraft will cover during the maneuver. In a three-dimensional perspective, the turn radius includes horizontal and vertical components. A purely vertical turn—such as a loop—has no horizontal turn radius but an entirely vertical turn radius. Both turn rate and turn radius are functions of the aircraft performance capabilities and depend upon airspeed, the magnitude and direction of the aircraft lift vector, and gravity. The relationship between rate and radius is complicated by the fact that the aircraft flight path vector does not necessarily respond directly to aircraft attitude changes.

Certain maneuvers can generate turn rate without creating a turn radius; and at the same time, large turn radii do not necessarily correspond to low turn rates. Due to this complex relationship between aircraft maneuver parameters, the debriefer finds it extremely difficult to describe accurately the magnitude and relationship of the various turn performance components. It is nearly impossible for the debriefer to determine accurately turn rate and turn radius using manual methods. Therefore, the debriefer must rely on rules of thumb and estimates, seriously degrading the accuracy of the debrief.

Two-Dimensional Presentation of Three-Dimensional Maneuvers

Manual methods challenge the debriefer to construct two-dimensional representations of three-dimensional maneuvers. Even the most highly skilled artist has difficulty producing drawings that accurately communicate the relative motion of the aircraft in three dimensions on a two-dimensional surface. This limitation seriously degrades the ability of the aircrew to perceive exactly how the maneuvers progressed and the relative effectiveness of each maneuver. In an effort to overcome this limitation, debriefers have developed special notation and abbreviations combined with "multiple view" drawings of the maneuvers. These techniques improve

the hand-drawn representations of the flight and allow the debriefer to estimate the value of critical position and performance indicators. Combining the drawings with the appropriate flight data completes the "picture" of the mission.

Maneuver Translation

In order to create a representation of a dynamic three-dimensional maneuver on a static, two-dimensional surface, the debriefer must alternate between top, side, and front views. Preparing these views is extremely time-consuming. The final product is susceptible to misperceptions and limited by the artistic skills of the debriefer. Oblique maneuvers (maneuvers that are a combination of horizontal and vertical maneuvers) are especially challenging, as the relative positions of the engaged aircraft change continuously in all three dimensions.

Limitation Summary

The complex and dynamic nature of aircraft maneuvering introduces serious data collection and presentation difficulties. Aircrews have resorted to numerous techniques in an effort to reconstruct the mission events during the mission debrief more accurately. As aircraft became more maneuverable and weapon employment tactics became more sophisticated, the debrief problems became increasingly difficult. As a result, aviators turned to technological solutions. Technology offered a way to record, transmit, and display the aircraft maneuvers automatically. The solutions became known as Air Combat Maneuvering Instrumentation or ACMI.

Notes

1. Aviators refer to aircraft acceleration in terms relative to the natural force of gravity. If a maneuver generates a force on the aircraft that is equal to twice the force of gravity, the force is described as "2 Gs." In this maneuver, a five-pound object would measure 10 pounds on a conventional scale. As the G force increases, the aircraft turn rate increases and turn radius decreases. Therefore, G readings provide vital information on aircraft performance.

Chapter 2

ACMI Concepts, Solutions, and Requirements and Limitations

In this increasingly competitive, often hostile and rapidly changing world, Americans seem to have only one real choice. Clearly our national well-being cannot be based on unlimited raw materials or on unlimited manpower and cheap labor. Rather it must be based on our ability to multiply and enhance the limited natural and human resources we do have. Technology thus appears to offer us our place in the sun—the means to insure our security and economic vitality.

—Dr. Malcolm Currie

ACMI provides the data required to overcome the limitations of manual methods. ACMI accomplishes this task by accurately determining aircraft attitude, position, velocity, and acceleration. These parameters are the essential components required to represent the three-dimensional characteristics of aircraft maneuvers. By continuously monitoring and recording these aircraft performance parameters, ACMI can provide a complete history of the aircraft trajectory in three dimensions. Manipulating this data and displaying graphic representations of the acquired parameters provides the debriefer with a motion picture replay of the flight. These motion pictures and the ability to rotate the scenes through any number of perspectives enables a two-dimensional screen to appear like a three-dimensional projection. These qualities of ACMI essentially solve the debrief problems and allow a more thorough and accurate debrief in less time.

ACMI Functional Requirements

The primary parameter required for ACMI functionality is aircraft position. The vast majority of the additional performance parameters can be derived from continuous measurements of aircraft position, although many are also captured as independent measurements. The accuracy of this position data and the rate at which it is measured drives the capability of the ACMI system. By determining the position of each participating aircraft, the distances, angles, and relationships between the aircraft can be calculated and displayed. Early ACMI systems relied on radio signals between the aircraft and ground stations to accurately determine aircraft position.

Time-Space-Position-Information (TSPI) Data

The original, non-GPS-based ACMI systems measured position through a combination of triangulation and radio-frequency transponder techniques. By employing multiple receivers on ground-based towers, the system

measured the arrival angle of the radio-frequency signals with special azimuth-sensitive antennae. Each receiver provides a single azimuth "cone" for each aircraft. Because each pod (and hence, each aircraft) uses a unique signal, the system differentiates between the signals from each aircraft. Combining the reception angles from numerous receivers refines the accuracy of the calculated position. This technique, referred to as Multilateration, or more commonly "Multilat," became the standard tracking scheme for early ACMI applications (fig. 6).

ACMI can also determine aircraft position using transponder techniques (fig. 7). By sending and receiving radio-frequency signals between the pods and the ground stations, the system can determine the distance from the aircraft to each tower. By "time tagging" signals as a series of independent pulses, the system can measure the time between the transmission of the

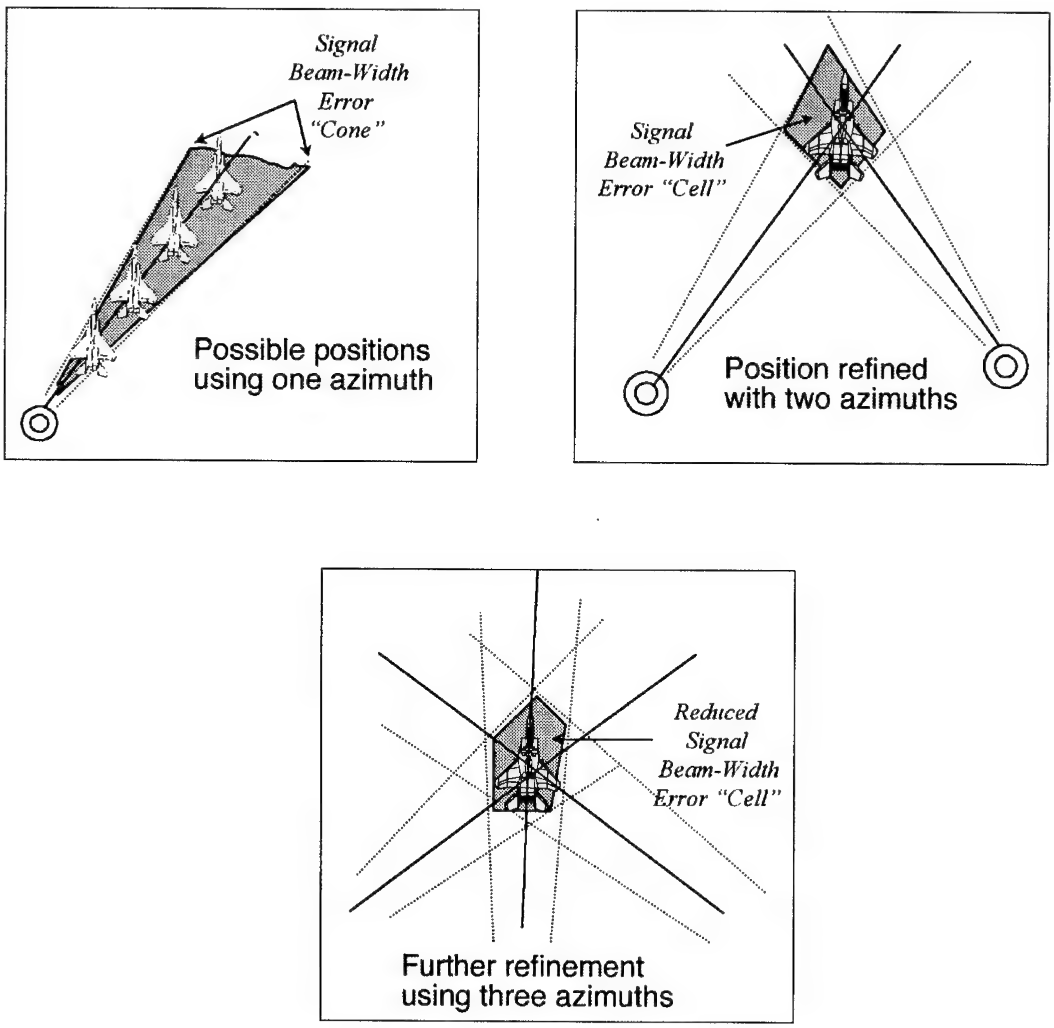


Figure 6. ACMI Position Using Multilateration Techniques

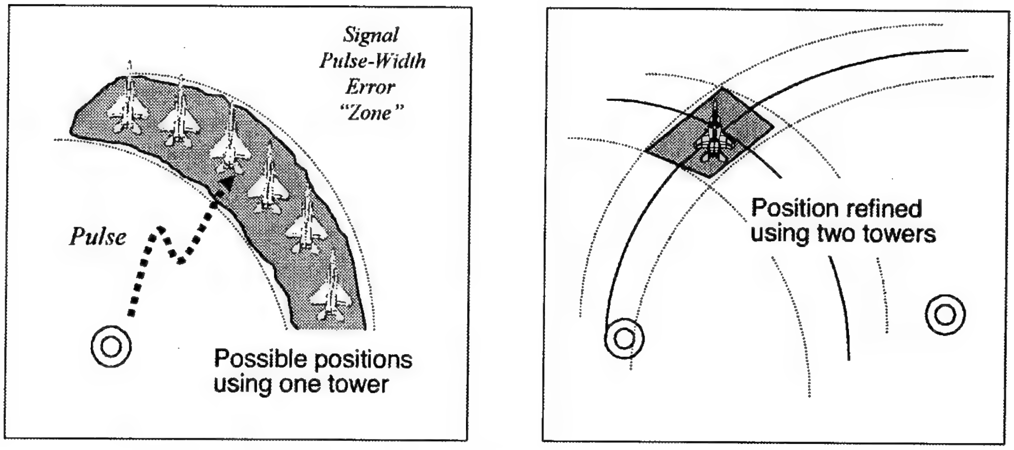


Figure 7. ACMI Position Using Transponder Techniques

pulse and the reception of the reply, or alternatively the pod can compare the pulse transmission and reception times. This time differential, combined with the known rate of transmission (for radio-frequency signals, the speed of light) determines the distance between the aircraft and tower. Instead of a series of azimuths, transponder techniques create a series of range arcs.

Velocity Data

Velocity data is another critical component of ACMI functionality. Although velocity data can be derived from position data (by calculating the derivative of position with respect to time), most ACMI systems rely on equipment similar to conventional aircraft pitot-static components. This equipment measures the aircraft airspeed by comparing the dynamic pressure of air entering a small hole in the front of a "pitot tube" with a separate, static pressure reading. The difference between these two pressures is proportional to the aircraft airspeed.

ACMI systems calculate and transmit velocity data as a function of true airspeed. Errors and limitations of this type of airspeed measurement that are not dependent on specific aircraft installation criteria are well understood and easily corrected. Applying the appropriate corrections provides additional performance parameters such as calibrated airspeed and Mach number.

Essential Aircraft Performance Parameters

ACMI also measures a wide variety of other essential aircraft parameters. These include three-axis accelerations, aircraft heading and altitude, and three-axis attitude components. These additional data sets complete the "picture" of the aircraft performance characteristics and allow the system to accurately calculate and display the data in combinations that fully describe the aircraft flight path. Aircraft altitude is measured using

aneroid equipment similar to that commonly used by aircraft altimeters. Acceleration and attitude data are also derived using common aircraft components including gyroscopes and accelerometers. Most ACMI systems also record radio communications transmissions between participating aircraft and ground or airborne control facilities.

Weapons Employment Data

More advanced ACMI systems also include the capability to monitor and display aircraft weapons employment data. These systems monitor signals carried on the aircraft weapons circuitry and interpret weapon status, launch, and release signals. By recording the precise time and position of the participating aircraft at weapons release, the system is extremely useful in determining the potential success of each weapon. Automated systems also include the capability to model weapon "fly out" characteristics and assign PK values against each target. If the weapon fly-out model determines that a missile would reach the target with a great enough PK, the system can tag the target as a successful engagement, or kill. Combining weapons release times and data with an accurate depiction of the distance and angles between aircraft greatly reduces the uncertainty of weapons employment events during the debrief.

ACMI Data Transmission, Encryption, and Recording

ACMI systems typically transmit the data to a central facility for decoding, recording, and display. The signal characteristics follow a prescribed data-link protocol that precisely controls the timing and sequence of the parameters in the data stream. The sensitive nature of the aircraft performance and weapons employment data requires the system to prevent unauthorized access to the data-link signals. Most systems use a standardized encryption technique to scramble the data and limit the potential for unauthorized access. By recording the data, the aircrew can replay the mission after landing or at any other time in the future.

Data Presentation and Display

By displaying the data in real time, the system allows ground observers to monitor and control the training missions, as well as provide suitable displays for a wide variety of audiences. These audiences may include additional aircrew members that can observe the mission and gather "virtual" experience for their own training. Ground observers can also function as "safety monitors." If the safety monitor perceives a dangerous situation developing—for example, an imminent aircraft collision—communications between the ground station and the participating aircraft provide a means through which observers can pass instructions for evasive maneuvers. Ground observers can also relay air traffic control

instructions, home field weather conditions, or any other information required by the aircrew.

The display system is the heart of the ACMI setup. Most systems use large, theater-sized projection screens that display the aircraft from a wide variety of perspectives or "views." The user can select from top, side, or an angled "oblique" view at any time. The system also provides virtual views from inside each aircraft cockpit, including left side, right side, forward, and rear views. These are particularly useful for evaluating the mission from each aircrew's perspective. The system also displays selected data for each aircraft, as assigned by the user. The user can choose a standard series of displays or create custom lists including the parameters required by each situation. This display capability eliminates the requirement for the aircrew to perceive, manually record, recollect, and recreate the mission events in the debrief. The accuracy of the aircraft position and velocity data also eliminates the uncertainty surrounding the performance of specific maneuvers and the resulting aircraft positions. Combining radio communications with the display completes the mission picture.

ACMI Limitations

Although extremely useful, ACMI systems do pose drawbacks. These include cost, complexity, transmission of sensitive classified data, and most importantly, the requirement for the aircraft to carry externally mounted pods. Until recently, the ACMI systems also required aircraft to fly over special ranges equipped with special transceivers mounted on towers. These characteristics fundamentally prevented fleetwide use of ACMI and relegated the system to occasional use in special operating areas.

Pod Requirements

All current US Air Force (USAF) ACMI systems—now referred to as Air Combat Training Systems (ACTS)—require each aircraft to carry a special pod. When the first ACMI system was developed in the early 1970s, the available aircraft used only the most rudimentary avionics equipment; and the data protocols within each aircraft varied widely between the different manufacturers. Additionally, the data available on the aircraft was insufficient to meet the needs of an ACMI data collection system. By locating the required equipment in a standardized pod, the system could serve a wide array of participating aircraft without requiring the user to customize the components for each aircraft type. By carrying pods, almost any aircraft could participate in the ACMI mission.

These pods contain all the required measurement, receiving, and transmission equipment in a single location on the aircraft. By designing pods to meet mounting requirements similar to those used by air-to-air

missiles, the pod manufacturers did not have to build custom configurations for each aircraft type. Any aircraft design with standardized missile mounting locations can carry the ACMI pod. These missile stations also provided access to the aircraft weapons circuitry, allowing the pod to monitor and transmit weapons employment data.

Pod Limitations

Although the use of external pods provides a standardized and convenient method for housing and mounting equipment required by ACMI systems, these pods present significant drawbacks. As external components, the pods alter both the radar reflectivity and aerodynamic properties of the aircraft. Loading a single pod on the aircraft also produces aerodynamic asymmetries, reducing aircraft stability. Pod designers have taken special care to produce pods that closely emulate the characteristics of air-to-air missiles, thereby reducing this negative impact. This special requirement, however, increases the cost of the system and limits the amount of space available for pod components.

As external stores, these pods must be mounted and checked prior to each flight. This procedure increases aircraft maintenance costs and manpower requirements. If the aircrew discovers a pod malfunction after engine start, most systems require an engine shutdown prior to removal, repair, or replacement of the failed unit. Reaccomplishing engine start procedures and preflight checklists can delay takeoffs and cause the crew to miss scheduled training events. Although convenient, using existing weapons mounting locations produces other negative side effects. Occupying a scarce weapons station means that ACMI pods will not be carried into combat. Consequently, aircrews cannot rely on renowned debrief and analysis capability provided by the ACMI systems. Mounting these pods on weapon stations also increases the wear on weapons release and mounting hardware and poses the potential risk of the pod falling off the aircraft during flight. This potential represents a significant risk to the aircraft structure, as well as to occupants or structures in the area where a lost pod would impact the ground.

The pods also represent increased maintenance costs for each mission. The components housed inside the pod are subjected to the full variety of accelerations and vibrations common in aviation environments. These conditions require extremely robust components, increasing the cost and weight of each component. Additionally, many of the components inside the pod are similar to those already mounted inside the aircraft, creating a duplicative cost of procurement and operation. The pods themselves must be routinely checked for proper operation and repaired if necessary, further increasing aircraft maintenance and manpower requirements.

Equipment Cost and Complexity

Current ACMI data transmission, processing, and display systems are extremely complex and expensive. The ACMI signals are typically transmit-

ted through special cables or repeated by additional ground stations for processing the host station. The host station requires special computer equipment to interpret and calculate the myriad of parameters used for the ACMI display. The host station must also provide means of recording and storing the data, most of which is typically treated as classified information. These combined factors drive the acquisition cost of a typical system into the tens of millions of dollars.

Ground Station Requirements

Until recently, ACMI systems required ground stations to communicate with the pods mounted on each aircraft. These ground stations had to be located on specific points and in specific patterns to optimize the accuracy and tracking capability over the ACMI coverage area. This requires the ACMI user to either purchase or lease the real estate required for land-based systems or—alternatively—build sophisticated floating or anchored mounting stations for over-water applications. Purchasing, operating, and maintaining these ground stations represented the greatest single cost factors for early ACMI systems. These ground stations also represent one of ACMI's greatest limitations.

Requirements for ground-based towers and relay stations limit the airspace available for ACMI missions. The aircraft must fly within a limited distance to ground stations to ensure radio signal reception. The frequencies available and the limited size and power of the radio transmitters inside the ACMI pods force the users to fly ACMI missions within relatively small, restricted airspace reservations. These restrictions prevent most aircrews from participating in ACMI missions on a regular basis.

Data Stream Encryption Requirements

The sensitive nature of the data included on the ACMI data stream requires sophisticated encryption techniques to prevent unauthorized access. By monitoring and analyzing ACMI mission data, adversaries could potentially deduce critical aircraft performance characteristics and weapons employment procedures and tactics. The requirement to scramble the ACMI signal reduces the throughput capacity of the data stream and increases the cost and complexity of ACMI components. The encrypted data stream must also be decoded at the receiving end, further increasing the cost and complexity of the host system. Updating the encryption codes on the ground stations, pods, and host system further increases manpower requirements. Although significant, this penalty is a fundamental requirement of a ground-based ACMI system.

Display System Requirements

To take full advantage of ACMI functionality, most systems use theater-sized displays and viewing rooms. These theaters also provide operations and monitoring consoles to operate the ACMI system. Display systems use

sophisticated projection and other computerized equipment to generate the complex depictions of the aircraft and associated maneuvers. This equipment must provide the capability to offer multiple view perspectives, as well as graphic rotation and multiple levels of zoom. The viewing theaters also include multichannel sound systems to broadcast various communications data associated with each flight. If the ACMI signal includes classified data, the display systems must be housed within special buildings or compartments cleared for open discussion and display of classified material. Each component used must also be cleared for classified data processing.

Chapter 3

ACMI System Development and Kadena Interim Training System

The development of a new weapon is generally hindered by a kind of enthusiasm that concentrates attention on maximum capabilities in performance. This particular kind of violation of the law of diminishing returns incurs the penalties [of two] mistakes—premature use and failure to exploit initial gains.

—J. M. Cameron

ACMI systems development has its roots in the Vietnam War era. During this period, USAF and Navy air combat units experienced a sharp decline in air-to-air kill ratios. Consequently, military officials searched for ways to improve air-to-air performance. Department of Defense (DOD) studies suggested that training effectiveness was to blame.[1] A Naval Air Systems Command report, the *Air-to-Air Missile System Capabilities Review*, known as the "Frank Alt Report," highlighted the need for improved training regimens and suggested improved methods for mission debrief.[2]

Genesis of ACMI Systems

In response to the findings in these studies, the USAF and Navy undertook programs aimed at improving training effectiveness and combat performance. Both services institutionalized formal combat training schools. The Navy program, now known as Top Gun, concentrated on close-in fighter combat training and eventually settled in Miramar, California. The USAF responded with the Fighter Weapons School founded at Nellis AFB, Nevada. The USAF also began an intensive training program at Nellis AFB that was to become Red Flag. These combat training programs required an improved debrief capability. Under Navy funding, the US Marine Corps (USMC) developed the first ACMI system to meet this need.

First ACMI Systems

The USMC contracted with Cubic Defense Systems to design and build the first ACMI system for Marine Corps Air Station, Yuma, Arizona, in 1973. The original system consisted of a series of seven ground-based tracking towers that communicated with pods carried on participating aircraft. The system tracked as many as eight aircraft simultaneously and provided real-time depictions of the aircraft throughout the flight. The pods carried by the aircraft served two functions—calculate and transmit aircraft performance data and report aircraft position. These two basic capabilities remain as the primary functions of pod-based ACMI systems.[3]

ACMI Maturation

The success of the initial ACMI systems spawned a series of new training airspace areas, or "ranges," designed to maximize utility of the new technology. Many of the new ranges capitalized on the benefits of operating over large bodies of water. The Air Force and Navy sponsored the construction of several ACMI ranges including locations in the Gulf of Mexico, the North Sea, the Mediterranean, and the Pacific. These over-water ranges offered the advantage of reducing the requirement to purchase real estate for the construction of the ground-based tower facilities. The system capabilities also expanded, eventually tracking more than 100 aircraft as well as monitoring and displaying weapons events. These new capabilities led ACMI missions to transition away from routine training and towards large-force exercises. This shift in focus generated new requirements for future upgrades on the existing systems. These factors combined to force designers to rely on external components. Satisfying an ever-increasing list of requirements across a wide array of aircraft could only be accomplished with external pods.

The ACMI ranges became virtual combat zones, tracking dozens of aircraft in realistic, high-intensity training exercises. The latest systems include the capability to monitor and score air-to-air and air-to-ground weapons deliveries as well as include ground-based threat systems and simulators. Although extremely successful, the systems maintained the requirement to rely on ground-based tracking towers and externally mounted aircraft pods. Cost of maintaining the ACMI equipment rose as well. The high cost of ACMI missions drove the systems towards specialized utilization and away from routine training. Although fully capable of enhancing even the most basic training mission, the small number of ranges and high cost of operating and maintaining the equipment prevented aircrews from using this capability on a day-to-day basis.

Kadena Interim Training System (KITS)

In 1993 a series of typhoons severely damaged the tracking towers used by the Kadena ACMI range located off the coast of Okinawa. Faced with tower repair costs in excess of $200,000 each and an operating budget that had grown to more than $6 million a year, the Air Force looked for an alternative to the ground-based ACMI system.[4] The USAF chose Cubic Defense Systems to develop a new ACMI technology that would not require the construction of ground-based towers. The new technology, known as Air Combat Training-Rangeless (ACT-R), eliminated the requirement for ground-based tracking towers by combining aircraft data-link and GPS technology.

A GPS-based position capability replaced the conventional tower-based tracking techniques, while the data-link signal allows communication between aircraft—or if desired—between the aircraft and an optional, mobile ground station. Free from ground-based towers, ACT-R missions can be flown in any airspace. In 1994 the USAF paid $9.7 million for the

development and delivery of 24 KITS ACT-R pods and four computerized display units.[5] This technology led to a DOD-wide implementation of GPS-based ACMI systems. By 1999 nearly every ACMI range added GPS capability, freeing the aircraft from the requirement to operate only in special airspace within broadcast range of ground-based towers.[6] No longer restricted to rare training opportunities in special airspace, aircrews can now use ACMI equipment to improve routine training. However, the limited availability of pods and associated processing and display equipment again prevents fleetwide application.[7]

The system requirements document mandated autonomous data-link operation, free from ground-based infrastructure. The document specifies the capabilities listed in table 1. To meet these requirements, Cubic Defense Systems designed a new ACMI pod as well as a new display system.

Table 1

KITS System Requirements Summary

General System Specifications			
Paragraph	**Sub-Element**	**Requirement**	**Functions**
3		Support for the F-15C/D and F-16C/D 30/40/50	Provide training for locally based aircraft
		Maximum of 24 aircraft	Enable full range of missions including large force exercises
3. a.		Time-space-position information (TSPI)	Provides necessary aircraft tracking data
3.a.		Correlate and process weapons events	Real-time kill notification and postflight weapons employment evaluation
3.a.(1)		Meet current weapon interface and loading standards	Precludes requirement to design and implement additional carriage procedures
3.a.(2)		Air-to-air data link, 65 nautical mile range, meeting existing frequency management procedures	Communications between aircraft and allows real-time monitoring
3.a.(3)		Weapon simulations	Realistic weapons employment training
3.a.(4)	-1	Autonomous data recording	Provide postflight review capability
3.a.(4)	-2	Relative position error less than 25 feet	Provide accurate aircraft position data
3.a.(4)	3	Storage for three independent one-hour missions	Allow multiple missions without requiring aircrew action
3.a.(5)		Meeting existing electronic security requirements	Precludes implementation of additional security measures
3.a.(5)	-1	Recording media easily removed and stored in existing approved security containers	Precludes implementation of additional security measures
3.a.(5)	-2	Unused pods contain no classified data	Precludes implementation of additional security measure
3.a.(5)	-3	Separation of RED and BLACK data	Prevents transmission of sensitive data
3.a.(5)	-4	Restricted data transmission	Prevents transmission of specified classified data (PK, missile launch envelopes, missile capabilities, and countermeasures)
3.a.6		Transportability on aircraft or in specified existing containers	Provides deployment capability without increasing logistical requirements

Source: System Requirements Document, KITS, Headquarters ACC/DR (USAF), 19 December 1994.

KITS ACT-R Pods

The KITS pods (fig. 8) represent the latest approach to ACMI functionality. These pods combine data acquisition, recording, and transmission capabilities in a single flight-certified unit similar in size and weight to previous ACMI pods. Like previous ACMI applications, the pod connects to the aircraft power and weapons circuitry through the air-to-air missile station umbilical. This connection provides weapons status and launch information, component power, as well as an audio interface channel. The pod collects aircraft performance data by combining the signals from an inertial navigation unit (INU), GPS position receiver, and an integrated air data sensor. The KITS pods store the mission data on solid-state, removable cartridges known as data transfer modules (DTM). Each DTM can hold up to three hours of flight data. The pods process the data for transmission across parallel superhigh frequency and ultrahigh frequency (UHF) data links.[8]

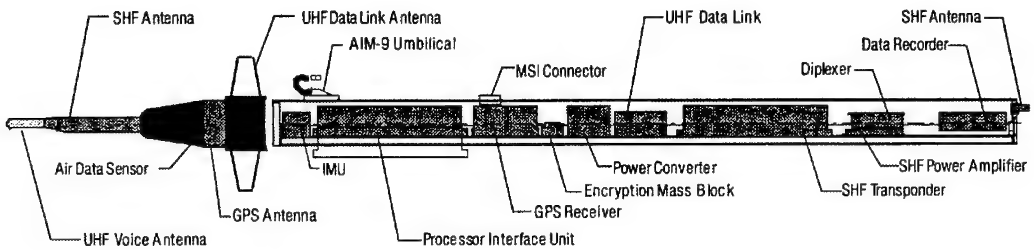


Figure 8. KITS ACT-R Pod

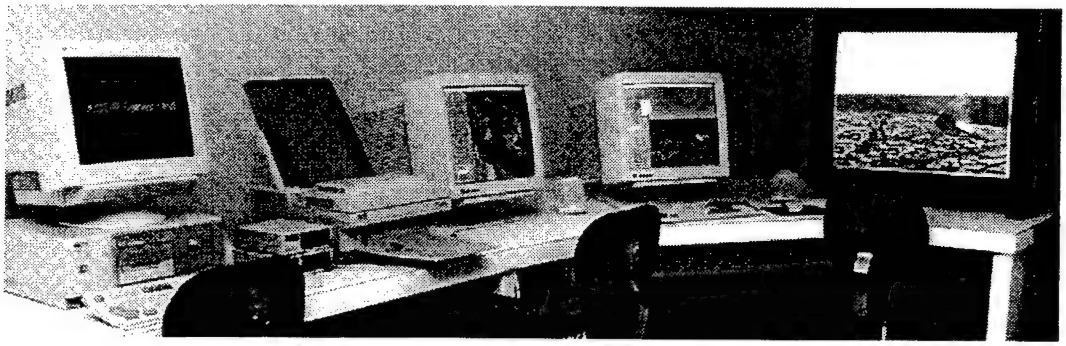
The pod also incorporates a special processor designed to calculate missile fly-out models. This processor meets the requirement for real-time kill notification by analyzing the weapons launch parameters and estimating the missile trajectory according to preprogrammed flight models. If the processor determines that the solution to missile fly-out routine results in an acceptable intercept to a participating aircraft, the engaged target is declared as a "kill." The aircrew in the target aircraft is alerted to this condition via the data link. The pod in the target aircraft generates an audio "kill" message to the aircrew headset.

The KITS system can track 24 aircraft simultaneously as well as 48 simultaneous weapon events, including four weapons from a single aircraft. The tracking and weapon event data is broadcast across an encrypted, parallel data-link channel received by all participating aircraft. Each pod records the entire flight data file on the removable DTM, allowing any single DTM to store and transfer all participating aircrafts' data.

KITS Processing and Display Station

The aircrew can extract the data from the KITS DTM cartridges using a customized processing and display computer station. This custom-built

computer console contains a conventional personal computer (PC) server, a Silicon Graphics workstation, eight-millimeter videotape player-recorder, and three display monitors.



KITS Processing and Display Station

By incorporating a computer-controlled videotape recorder, the system can simultaneously display aircraft HUD, weapon, or gun-sight video along with ACMI presentations. The user can also record displayed images on the system videotape recorder. The ACMI presentations include conventional ACMI perspectives with three-dimensional, filled renderings of aircraft, terrain, and weapons. The system also provides long-term data storage capability that allows aircrews to review the processed data at a later time.

The KITS software runs on the Unix operating system installed on a custom-built Silicon Graphics workstation. The graphics subsystem allows the user to display any perspective from any aircraft—including aircraft videotape—on any screen, as well as a combined screen divided into four separate windows. Aircraft parameters such as airspeed, altitude, and range data are also available in user-defined lists and tables. The system also incorporates a "what if" scenario function, known as a "hypothesizer," that allows the operator to modify recorded weapons employment parameters to evaluate alternative potential outcomes. This feature displays what *would have* happened if the aircrew had launched weapons at different times during an engagement.[9]

Notes

1. Paul Burbage et al., *Air Superiority Tactics over North Vietnam, 1964–1972*, USAF Southeast Asia monograph series (Maxwell Air Force Base [AFB], Ala.: Air Command and Staff College, 1975), 120.

2. Naval Air Systems Command, *Air-to-Air Missile System Capabilities Review*, November 1968, Defense Technical Information Center, AD-A955142.

3. "First Range Less Air Combat Training System From Cubic," *Asian Defense and Diplomacy*, June 1998, 46.

4. Lt Col Frank DiGiovanni, Headquarters ACC/DR, telephone interview by author, 31 January 2000, Maxwell AFB, Ala.

5. Paul Seidman, "Free Range," *Flight International*, 16 December 1998, 27.

6. Lt Col John D. Jannazo, AFMC/ RISPO, telephone interview by author, 27 March 2000, Maxwell AFB, Ala.

7. Lt Col R. Kent Laughbaum, 48 FW/DP, telephone interview by author, 29 March 2000, Maxwell AFB, Ala.

8. Cubic Defense Systems, ACT-R System Specifications data sheet, February 1999.

9. Alex Koenig, Cubic Defense Systems, telephone interview by author, 17 March 2000.

Chapter 4

Proposal for Internal Solutions

Know and use all the capabilities in your airplane. If you don't, sooner or later, some guy who does use them all will kick your a- -.

—Dave "Preacher" Pace

Within the limited scope of providing basic ACMI functionality on every aircraft for routine training missions, designers can capitalize on avionics capability currently installed on modern fighter aircraft. In fact, a rudimentary capability already exists. Many aircraft, including civilian airliners, use flight data recorders that monitor and record aircraft performance parameters similar to those used for ACMI. These systems produce data files that are easily processed and displayed on modest computer systems. The scenes available are often used to recreate the aircraft flight profile following mishaps or for accident prevention and investigation. Expanding this concept can provide basic ACMI functionality. Advanced ACMI features can be produced with only minor modifications to existing components.

By increasing the data collection rate to compensate for the dynamic nature of fighter combat maneuvering, storing the data on removable cartridges, and leveraging the display capabilities currently developed for modern PC-based flight simulation and game software, Air Combat Command (ACC) can acquire basic ACMI functionality at a fraction of the cost of current and proposed systems. Although the current avionics capabilities are not ideal for large force employment exercises, an internal solution offers significant and desired training benefits across a much broader spectrum of training missions. Even more importantly, the benefits can be made available for every aircraft on every mission, including combat missions.

The avionics architecture and bus parameters available on the F-15E aircraft exemplify the untapped potential currently residing on today's aircraft. This example highlights the feasibility of the proposed internal system. The following describes the parameters available on the F-15E aircraft and compares these parameters to those required by ACMI systems. Similar parameters are available on other modern fighter aircraft.

Previous Attempts at Internal Systems

Early attempts to design and install internal ACMI systems failed. Although these systems were conceived considering many of the same factors identified in this research, avionics components and computing

power limitations prevented adoption of the systems. At the time previous systems were developed, Global Positioning System (GPS) equipment was not available. Evaluators determined that inertial navigation system (INS) components did not provide position data accurate enough for ACMI applications. Additionally, PCs did not have sufficient processing power or graphics display capability. The recording media available were not suitable for ACMI purposes. These factors have been overcome by recent advances in avionics and PC technology.

Success Criteria

To determine if the proposed system would warrant a full-scale concept development, program success criteria were developed. Failing to meet these criteria would indicate that an internal system would have limited potential to meet operational requirements and present a favorable alternative to the current pod-based systems. Note, these criteria were developed for comparison of a basic system and do not necessarily reflect the potential for an internal system to replicate systems used in large force training exercises or capabilities required by the Joint Tactical Combat Training System (JTCTS).

Table 2

Success Criteria

System operates on noninterference basis —system cannot interfere with the operation of any other installed equipment
Displays accurately reflect aircraft performance —inaccurate or jumpy animations would not be useful
Software usable on typical squadron PCs —requirement for special equipment increases cost and complexity
Recorder and monitoring equipment inexpensive and easily installed —difficult installation or cost prohibitive components reduces acquisition potential
Similar to ACMI but at greatly reduced cost —system must replicate most ACMI features except high cost
No negative training aircrew workload —ideally, the system would require no aircrew action for operation
Recording media widely available —media must be nonproprietary common components
Data requirements allow adequate recording time —minimum of two hours recording time
System requires minimal user training —if the system is too difficult to operate, it will not be used
No significant increase in classified material —squadrons possess only limited storage areas
System design responsive to user input —software must be tailorable to user needs and requests

Recent Technology Advances

Current technology offers the potential to overcome the shortfalls identified in the earlier attempts to install internal ACMI equipment. GPS equipment is now common. Data-link equipment—commonly referred to as Fighter Data Link (FDL)—allows aircraft to share valuable information. PC calculation and graphics display capabilities rival the power of last year's custom-built graphics workstations. Solid-state recording devices based on the PC 104 architecture have replaced analog tape equipment. In fact, these are the same technologies that freed pod-based systems from relying on ground-based towers. Combining these technologies offers a potentially viable internal solution.

GPS Equipment

GPS equipment now provides accurate aircraft position data anywhere on the globe. GPS receivers that are widely available in many aircraft currently include this equipment. Military aircraft are equipped to receive and decode the more accurate encrypted signal, providing position data accurate to 10 meters. Both the F-15 and F-16 aircraft have demonstrated GPS capability, and it is highly likely that all these aircraft will eventually be equipped with GPS receivers. This equipment will form the backbone of an internal ACMI system.

Fighter Data Link

The data-link concept began as the Joint Tactical Information Display System (JTIDS). The system was installed on a small number of tactical aircraft, including the F-15. Although the system proved highly effective, equipment cost prevented fleetwide distribution. USAF planners have supported the development of a low-cost alternative to the JTIDS system. This new system, now referred to as FDL, offers the potential to replace the data transmission equipment currently used in pod-based ACMI systems. In this way, FDL will enable advanced ACMI features for internal systems.

PC 104 Architecture

The drive to design and manufacture components compatible with laptop computers fostered the adoption of a new component protocol known as PC 104. This specification forms the basis for the development of an entire family of devices that capitalize on the latest miniaturization technology. The specifications spawned two significant components—interchangeable circuit boards and CompactFlash memory cards. These devices allowed avionics component manufacturers to design circuit boards according to a common standard and paved the way for miniature solid-state recorders and storage devices. These technologies facilitate the development of standardized 1553 bus interfaces and miniature "PC Card" storage cartridges. These devices are essential components in current

pod-based systems and provide a readily available alternative for an internal system.

Avionics Requirements and ACMI Parameters

Modern avionics components can provide basic ACMI functions. What is not normally installed involves equipment needed to record and transmit ACMI data. If the user does not require real-time display of the ACMI signal and real-time kill notification, transmission equipment is not necessary. For training missions that do not require these functions, basic ACMI functions can be performed using onboard avionics with only a minor modification to install and connect a monitoring and recording device. These devices would monitor and record data flowing on the aircraft 1553 bus circuits. The 1553 bus is the military standard communications link between avionics components. These circuits contain all the internally derived data in a special, efficient format ideal for recording. Sending the data to other aircraft, as required for mission observation and real-time kill notification, would require modification of existing FDL components.

1553 Avionics Data Bus

Modern aircraft avionics components are highly integrated and rely on high-speed, digital communications. To meet this requirement, engineers designed a robust intercomponent data path known as a "data bus." For military aircraft, these buses conform to the Military Standard (MIL STD) 1553. This standard specifies the characteristics of a two-way signal protocol that allows avionics components to communicate by sending discrete pieces of data (called parameters) across the bus. Physically, the bus consists of small diameter triaxial cables between components.[1]

The data stream consists of digital "words" that contain the numeric values and "labels" that identify the type and length of each parameter transmitted on the bus. In this fashion, any avionics component connected to the bus can transmit or receive data as required to carry out necessary calculations. Designers "package" the parameters on the 1553 bus by specifying discrete time slots or "cycles" for data transmission. The length of the cycle determines how often the data can be accessed. The cycle time establishes the maximum "refresh" rate for data on the bus. Each package contains a complete set of data.[2] At the end of each cycle, each component on the bus can update the parameters to reflect current conditions.

F-15 Avionics Bus Architecture

The F-15 uses MIL STD 1553 avionics buses for data communication between the avionics components (fig. 9). This bus architecture uses a combination of 16- and 32-bit "words" to transfer data between the central computer and other associated avionics components. The data on the 1553 bus is refreshed every 50 milliseconds, and the parameters are

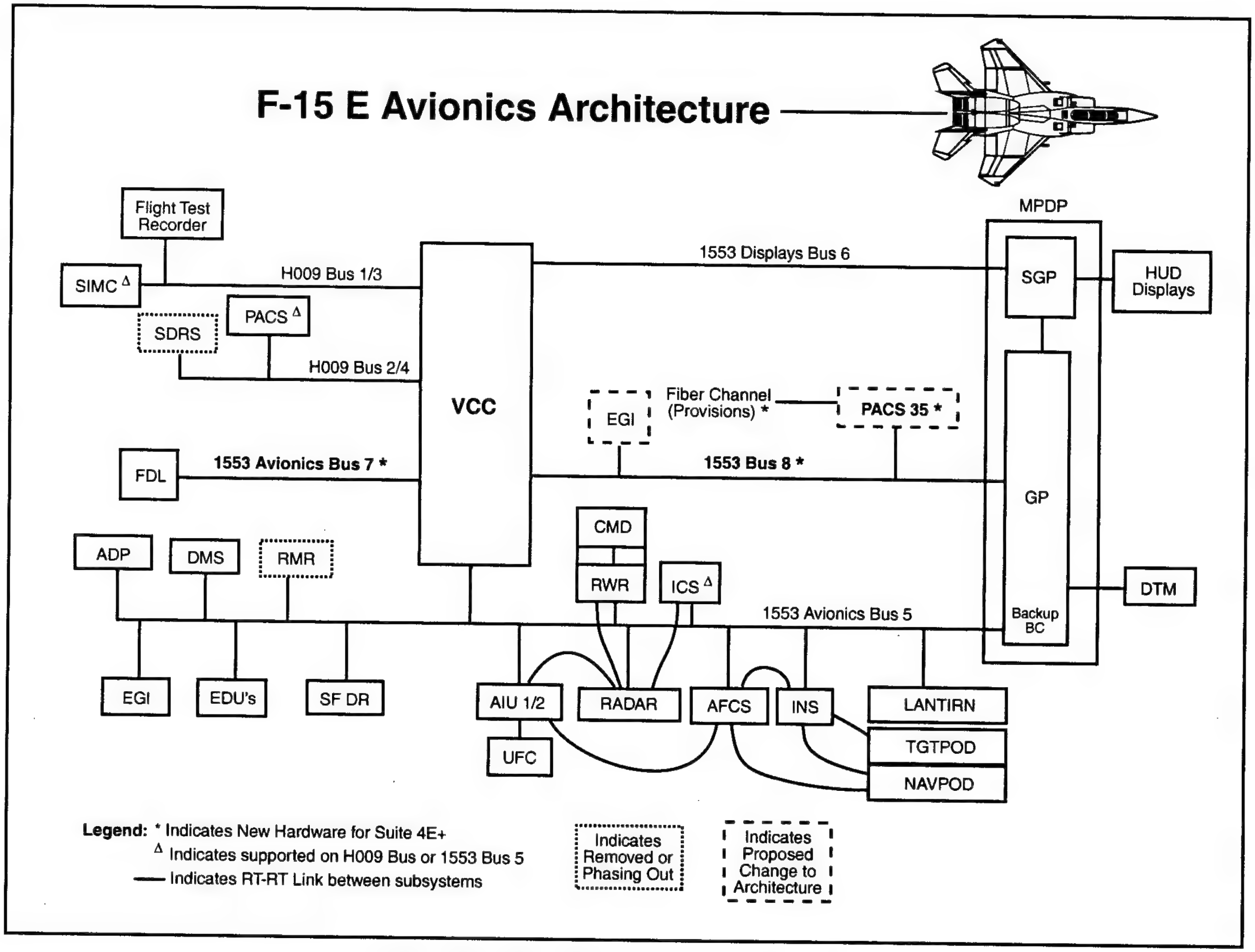


Figure 9. F-15E 1553 Avionics Bus Layout

shared across five separate buses. Monitoring and recording the signals on these buses can provide the data necessary for basic ACMI functions.

F-15 Aircraft Performance Parameters

F-15 avionics components calculate the aircraft performance parameters required for ACMI functionality. The accuracy of the data calculated by onboard avionics is accurate enough for safety of flight and weapons employment calculations. This level of accuracy is more than sufficient for ACMI purposes, and in many cases internal aircraft data is much more accurate than what is currently computed by pod-based systems.

Aircraft Position

Aircraft position is determined by a blended solution of the onboard INS and GPS avionics. This data is continuously available on the 1553 avionics bus and is refreshed every 50 milliseconds. This refresh rate is nearly one order of magnitude greater than what is currently used by ACMI systems, and the blended solution is much more accurate than any single source. The position is reported in four 32-bit words comprised of time and X, Y, Z components. On the F-15E, the blended solution heavily favors the output of the aircraft embedded GPS/INS (EGI) with an accuracy less than 10 meters of spherical error using the military encrypted GPS signal. For periods of extreme maneuvering or when the GPS antenna is blanked by the aircraft structure, the system automatically filters the solution and favors the more accurate INS data.

This is a time-proven approach and one that is emulated by pod-based systems. However, many pod-based systems use only the civil GPS signal, accurate to 30 meters spherical error. The civil signal is also more prone to jamming and interference and can generate errors in the 100-meter range depending on satellite location and atmospheric conditions. In order to receive the more accurate military signal, these pods would require installation and programming of the military decoding components. Installing and updating this equipment represents another duplication of avionics already on board the aircraft, as well as increasing ground maintenance action requirements necessary to program the military encryption keys. Alternatively, pod-based systems offer a differential GPS corrective capability. This method requires a ground unit to transmit the differential GPS signal, again forcing the pod-based systems to rely on ground units.

Aircraft Velocity

Aircraft velocity data available on the 1553 bus includes calibrated and true airspeed measured by the aircraft pitot static system, as well as ground speed derived from either the EGI or INS system. Aircraft calibrated and true airspeed measurement accuracy is roughly equivalent to that measured by ACMI components, although somewhat more accurate due to the corrections applied to compensate for known airstream disturbances

caused by aircraft structural components and sensor installation misalignments. These corrections are particularly useful in the transonic region. Pod-based systems lack these corrections, primarily due to the fact that a pod can be installed on a number of different aircraft. Any correction coefficients would have to be developed for multiple platforms on numerous locations. The ground velocity data is unique and is not calculated by current ACMI systems. This velocity data may be useful for display purposes or calculating specific turn radius information.

Aircraft Altitude

Aircraft altitude data is available from three independent sources. This parameter is measured by the aircraft pitot static system, with an accuracy similar to the data measured by ACMI pods, noting the corrections previously mentioned. Altitude data is also calculated by the EGI and INS. This parameter is reported as a vertical or "Z-axis" component of the aircraft position. The absolute value of the INS data is less reliable due to the inherent inaccuracies of measuring vertical velocity with inertial navigation components; however, the altitude change rate accuracy exceeds that of pitot static measurements due to lag times and response delays associated with mechanical devices.

Altitude data is also available from the EGI system; and similar to the INS data, this parameter is reported as a component of aircraft position. Of the three sources, the GPS parameter is the most accurate, although the pitot static source is sufficient except during brief periods when the aircraft operates in the transonic flight regimes. Although the aircraft altitude parameter is roughly comparable to the pod-based value, the internal data offers a distinct advantage. Aircraft altitude is used by numerous aircraft avionics for weapons delivery and sensor cueing. Using the onboard value can aid in assessing weapons delivery and avionics functionality without introducing additional errors from externally derived altitude values.

Aircraft Heading

Aircraft heading data is available from three sources on the 1553 bus. The magnetic heading of the aircraft is measured by standard magnetic flux valve equipment installed in the tail of the aircraft. Aircraft heading is also determined by the INS. The system reports the aircraft true heading relative to geographic true north and corrects for magnetic variation by adding or subtracting the appropriate value listed in a worldwide magnetic variation table stored in the central computer. The EGI system also calculates aircraft heading. The EGI uses true airspeed, ground velocity, and position data and calculates vector components including ground track, drift, and heading. Any of these sources are adequate for ACMI functions. Pod-based systems have no direct heading measurement capability and must rely on position information derivatives to calculate heading. During periods of extreme maneuvering, aircraft heading can change

rapidly with only minor changes in position. Lacking a direct heading measurement causes externally derived heading values to misrepresent the actual aircraft heading. This error will result in erroneous depictions of the aircraft heading on ACMI displays. Using internal heading measurements eliminates this error.

Aircraft Attitude and Acceleration

Aircraft attitude and acceleration data is derived by the INS and EGI. Attitude data is reported as a series of three angles (pitch, roll, and yaw) representing the aircraft attitude relative to a localized, earth-centered axis system. These angles are reported as Euler angles on an aircraft-centered coordinate system referenced to the local horizontal and true north axes of the aircraft at start-up. The data is calculated by measuring accelerations and integrating the signal to provide rate data. An additional integration transforms the rate data into angular position data that represents the difference between the aircraft attitude and the fixed axis. Rate data is also calculated by independent pitch, roll, and yaw rate gyros. Linear acceleration data is reported directly from the measured signals along the same three axes.

Pod-based systems use a similar approach with similar accuracies with a notable exception. Because the pods are not mounted near the aircraft center of gravity (COG), the radial acceleration values can be in error as a function of the distance from the aircraft COG. Additionally, the pods are typically mounted on the aircraft wings. During extreme maneuvering, wing flexure and vibration can generate noisy acceleration signals that must be filtered. Filtering schemes can introduce errors and delayed responses at a time when accurate representations of the aircraft maneuvers are most important.

The internal values are used by the aircraft flight control computers. By recording the internal values, it is possible to evaluate flight control responses to pilot input during extreme maneuvering. Understanding and predicting flight control surface responses can assist in explaining how and why the aircraft responded to flight control inputs in highly dynamic situations. Pod-based systems do not provide this capability.

Weapons Data

Weapons engagement envelopes and launch signals are also reported on the 1553 bus. These parameters include missile minimum and maximum ranges, estimated times of flight, and conditions at launch. This data is available for all types of weapons loaded on the aircraft and is instantaneously displayed for the weapon selected by the pilot. At launch the target parameters reported by the radar are also available. These parameters provide the data necessary to calculate missile engagement and fly-out models, the key capability desired in advanced ACMI systems. Pod-based systems do not have access to onboard weapons data and must rely on independently programmed weapons models.

Current ACMI pods require the users to preprogram the processors with independent fly-out estimates and weapons loads. These independent algorithms introduce the potential to create mismatches between onboard calculations and those carried out by the pod computer. Independent models can calculate different weapons delivery solutions. The target may appear "in range" to the aircrew using the aircraft internal model, while the pod-based estimate can show the target as "out of range." The acknowledged existence of this error is currently preventing the aircrew from using the "automated kill notification" feature.[3] Eliminating this error potential is a key factor favoring internally based systems.

Performance Parameters Summary

The data available from internal sources meets all the requirements for ACMI functions. In every case the onboard data is at least as accurate as the externally derived values and in most cases is more accurate. Weapons data are not available from external sources and must be estimated and preprogrammed. These factors support the desirability of an internal system. Table 3 summarizes the key parameters for ACMI functions.

Table 3

Required Aircraft Performance Parameters Summary

Parameter	ACMI Source	Internal Source
Position	Pod GPS or pod signal	Aircraft GPS/INS
True airspeed	Pod pitot static system	Aircraft pitot static system
Ground speed	Pod GPS or INS	Aircraft GPS/INS
Altitude	Pod GPS or pitot static system	Aircraft GPS/INS or pitot static system
Heading	Pod GPS or INS	Aircraft GPS or magnetic heading
Attitude	Pod accelerometers	Aircraft GPS/INS
Acceleration	Pod accelerometers	Aircraft GPS/INS
Weapons data	Models and estimates	Aircraft weapons bus data

Expanded Features

Internal data also offers the potential to greatly expand ACMI functionality. In addition to the features currently available, internal data can provide new features such as display of aircraft radar coverage, targeting decisions, jamming effects, and sensor cueing (fig. 10).

Aircraft flight control inputs as well as throttle position could also be recorded for evaluation. These features would require the system to monitor and record additional parameters, but this expansion is well within the capability of the proposed system. Appendix A lists some of the additional parameters available on the F-15E. Many of these additional features are not available on current or proposed pod-based systems.

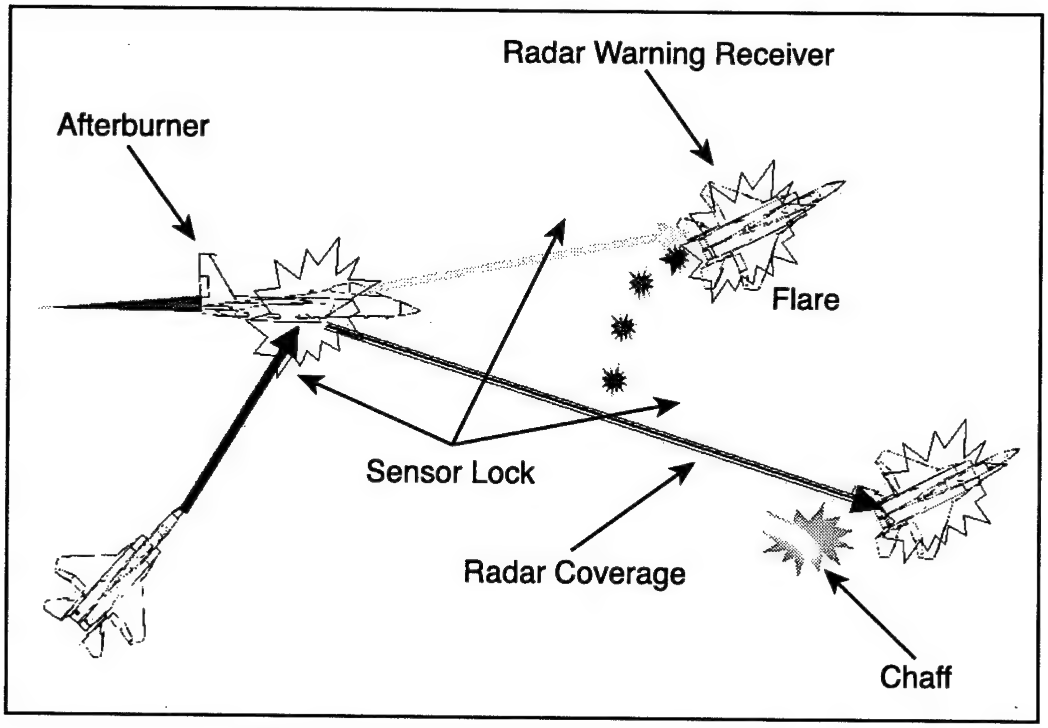


Figure 10. Expanded Features Presentation

Data Monitoring and Recording

Collecting the data available on the avionics bus is accomplished through a procedure known as bus monitoring. Bus monitoring is the process by which parameters on the bus are identified, intercepted, and stored. This process is already in use on all commercial passenger aircraft as well as selected combat and developmental test aircraft. The so-called flight data recorders, which are so critical in reconstructing aircraft accident events, are simple bus monitoring and recording devices. Two different bus monitoring schemes are available, monitoring all or part of the data.

Programmable and MUXALL Bus Monitors

Programmable bus monitors allow the user to select specific parameters at specific rates to collect only desired data. This method minimizes storage capacity required for recording and reduces postflight processing time. This method is slightly more complicated in that the bus monitor must be programmed to select only the desired parameters. The user must also determine an appropriate monitoring rate to ensure the data collected accurately represents the aircraft motion while at the same time preventing overload of the recording system. Alternatively, a MUXALL monitor can be used. This device records all parameters on the bus as they appear in real time. This method offers the advantage of reducing the potential to overlook critical data; however, this scheme greatly increases

storage capacity required and forces the crew to "strip off" the required data postflight. Special postflight processing software can automatically select and transfer the parameters from the MUXALL data set to a reduced file customized for a particular mission. If a MUXALL device is desired but the resulting data rate exceeds storage capacity, a "data pump" scheme can eliminate extraneous data.[4]

A data pump is a small software algorithm loaded in the aircraft central computer program. This algorithm directs the central computer to report, or "pump," specific values on a specific bus. By monitoring this bus, only desired parameters would be recorded. This scheme offers the additional advantage of reducing the number of buses connected to the bus monitor and providing data that may not be normally carried on the 1553 bus. By using a data pump, the bus monitor can be connected to only a single bus and still collect all the required data. This minimizes the complexity of the bus routing and connection design while introducing only a minor central computer programming modification. This technique is already employed by flight test data recording systems.[5]

Data Recording

Once the method of bus monitoring is determined and essential parameters accessed from the bus, the data must be stored on an appropriate media for postflight processing and review. Numerous recording methods are available. Most methods record the data exactly as it appears on the bus, although some use a data compression scheme to increase storage time. The recorded data formats include the combination of time parameters, 16- and 32-bit words, and other signals that make up the avionics data stream.

The bus monitor can be paired with either a tape-based or pure digital recording device. Analog and digital tapes offer the advantage of inexpensive media, common playback and recording equipment, and simple scalability. The tapes are resistant to shock and vibration and offer reliable long-term storage potential. Pure digital recordings offer the advantage of reduced media size and resistance to temperature conditions. These solid-state recording devices are also more reliable with fewer moving parts and no potential for tape malfunctions. Many are paired with a dedicated processor that formats the data. This processor can also run independent software routines useful for an internal ACMI system. In some pod-based systems, this processor actually calculates the missile fly-out models.

The current trend is a shift away from tape-based recording media—such as those found on many airline flight data recorders—towards the more reliable solid-state devices.

Modern fighter aircraft such as the F-15E currently use a number of solid-state digital recording cartridges for avionics programming and mission debriefing procedures. For internal ACMI functions, a solid-state CompactFlash card is the most promising alternative. These devices are available in a number of different storage capacities and configurations,

and methods for extracting the data are already established. In fact, the proposed internal system could use the device currently installed in the KITS pod.[6]

Requirements for Advanced Features

Although basic ACMI functions do not require aircraft data transmissions, advanced features such as automated kill notification and real-time monitoring of the flight would require some method to transmit the data to other aircraft. Automated kill notification and real-time flight monitoring capability will require hardware and software modifications to the aircraft.

Data Transmission and Automated Kill Notification

Several methods could be employed to transmit the data between aircraft or to ground-based relay or reception stations. In most aircraft, UHF or very high frequency radios are installed that could be modified to transmit the internally derived data stream, or a separate transmitter could be installed that shares the existing antennas. Alternatively, an internal solution could capitalize on recent developments in the fighter-to-fighter communications technology available on the F-15 FDL.

Leveraging Fighter Data Link

The FDL offers secure, encrypted fighter-to-fighter and fighter-to-ground communications. The system currently transmits and receives a wide variety of data between aircraft with multiple levels of security. The data includes position information of all participating aircraft, an essential component for weapons engagement and fly-out model resolution. The signal is encrypted and offers transmission and reception ranges in excess of 50 miles.[7] This device is also connected to the 1553 bus. The system transmits aircraft position and other important data across a wide-area secure data link suitable for an internal ACMI solution. For training use, the data-link protocol can be modified as necessary to meet the needs of the desired ACMI functions.

The FDL components also offer expansion card capability, useful if extra processing is required to calculate missile fly-out modeling or other tasks.[8] By installing a dedicated processor, the missile fly-out models and PK calculations can be handled without increasing the demands on the aircraft central computer. Storing the fly-out model algorithms in this extra processor also provides the option to emulate a wide range of missile systems, including classified and unclassified routines. These routines can be programmed to match the routines used by the debrief system, allowing for completely unclassified missile fly-out model display and recording. Although these additional models can reintroduce weapons parameter mismatch issues, the capability to operate in an unclassified mode may outweigh the potential mismatch issues. Adding an additional processor to the FDL system also provides custom configuration capability.

The FDL currently receives programming instructions from the aircraft DTM. By modifying the programming instructions, the aircrew can direct the new processor to use specific fly-out models and PK values for specific missions. This option would allow the crew to choose between classified and unclassified results on every mission. Additionally, if the fly-out models and PK values were included as part of the FDL instruction set, the aircrew could load the models directly. This would allow the introduction of new models as needed for weapons modifications or the emergence of new systems.

By storing the weapon fly-out models on the additional FDL processor, automated kill notification can be accomplished on the target aircraft. By hosting the fly-out model on the target aircraft, the processor only requires missile launch and update parameters. This data consumes only a fraction of the bandwidth compared to transmitting the model itself. The bandwidth consumption ends when the "shooter" aircraft stops supporting the missile. From that moment on, the target aircraft processor can continue to run the missile fly-out algorithm and determine PK.[9] Alternatively, the fly-out model can run on the shooter aircraft.

By monitoring the position of the target aircraft, the FDL processor can determine PK on the shooter aircraft. The processor can execute the fly-out model at launch and throughout missile support, and when the model predicts an acceptable intercept, send a "kill" message on the FDL. This technique reduces the data transmission requirements and further disguises missile performance data. The data-link signal contains only the kill message and no data on what aircraft launched the missile or at what time or range the missile was launched.

Automated kill notification requires an additional modification of the aircraft central computer operational flight program (OFP). The aircrew requires a visual or aural cue to notify them if they are assessed as a kill. This can be accomplished by directing the aircraft avionics interface unit (AIU) to release an existing audio message, or alternatively, the AIU could be programmed with a new message indicating a successful engagement in the target aircraft. If a visual display is desired, the central computer OFP could be modified to generate a custom graphic on one or all of the aircraft multipurpose displays. This graphic could also be combined with an audio cue.[10]

These features would also necessitate a modification of the FDL hardware and Link 16 message protocol. As an alternative to modifying the FDL component, the aircraft central computer could be reprogrammed to calculate the weapon fly-out models and send a kill notification message to the FDL. This option would reduce the hardware modifications; however, it would likely require a deletion of existing avionics features to free up memory space and processing time required for missile fly-out calculations. Alternatively, the system recorder could include a processor to perform these tasks. This type of recorder is already in use on some pod-based systems. Table 4 lists the modifications required for these features.

Table 4

Modifications Required for Advanced Features

System	Hardware Modifications	Software Modifications	Integration Requirements
Option 1—FDL Modification			
Fighter Data Link	Additional Processor	FDL OFP, FDL of message protocol, aircraft CC OFP	AFMSS programming, Link 16 message standard
Aircraft DTM	None	Readdressing memory locations	Aircraft CC OFP, AFMSS programming, C-Bits programming
Aircraft AIU	None	Kill message recording	Aircraft CC OFP, AIU OFP
Multipurpose Display Processor	None	Kill display programming	Aircraft CC OFP, MPDP OFP
Programmable Armament Control Set (PACS)	None	Additional weapons programming	Aircraft CC OFP, MPDP OFP, AFMSS programming
Option 2—Aircraft CC OFP Modification			
Aircraft CC OFP	None	Addition of weapon fly-out routines	AFMSS programming, Link 16 message standard
Aircraft DTM	None	Readdressing memory locations	Aircraft CC OFP, AFMSS programming, C-Bits programming
Aircraft AIU	None	Kill message recording	Aircraft CC OFP, AIU OFP
Multipurpose Display Processor	None	Kill display programming	Aircraft CC OFP, MPDP OFP
Option 3—"Intelligent" Data Recorder with Built-In Processor			
Aircraft CC OFP	None	Data pump to recorder bus	Link 16 message standard
Aircraft DTM	None	None	None
Aircraft AIU	None	Kill message recording	Aircraft CC OFP, AIU OFP
Multipurpose Display Processor	None	Kill display programming	Aircraft CC OFP, MPDP OFP

Internal System Feature Summary

Combining internal data with a modified FDL system can meet all the requirements for advanced ACMI functionality. Fully automated kill notification would require minor modifications to the aircraft central computer OFP. Including the data pump would also decrease data storage requirements, simplify hardware installation, and streamline the post-processing routine. The KITS data recording equipment as well as the weapons fly-out processor can be adapted for internal use, or a new design can be implemented based on the KITS components. Adding the programmability feature through the FDL instruction set would add a highly desirable measure of flexibility requiring only a minor DTM programming modification. Any or all of these features can be included as part of the internal ACMI solution.

Basic ACMI features can be installed without modifying aircraft software. Hardware modifications are limited to the work necessary to mount the components and connect to the data bus. Advanced ACMI features do not require extensive modifications but must be chosen commensurate with the effort required to update individual components. The most significant aspect of the internal solution corresponds to the ability to greatly expand traditional

ACMI functionality. By monitoring internal signals, users can tap into a wide variety of parameters unavailable to pod-based systems and further improve training opportunities. These modifications could be released as components in a software suite release to minimize the software integration testing requirements typically addressed in any change to the aircraft OFP.

Data Presentation

Once the data is collected, presenting the data can be accomplished using the methods already developed for current ACMI systems. The data can be manipulated to replicate the exact ACMI file format for use on existing ACMI equipment. For commonality, the user may purchase additional KITS stations (without purchasing the pods) and process the internal data using the KITS equipment. If the user wishes to view the data without using ACMI host equipment, the files can be transferred and processed on typical PCs. This technique can leverage display capabilities and routines currently used in PC-based flight simulators and aerial combat games. Alternatively, the KITS source code can be ported to a PC-based operating system and software suite.[11] If users deem the sensitivity of the data requires special handling, the files and equipment can be protected using established classified computer processing procedures.

Data Post-Processing Requirements

The recorded data must be processed for use by the display system. The aircraft position and attitude data must be translated into a graphic representation similar to the process used by current ACMI systems. If the data-collection refresh rate was reduced to increase storage capacity, the files may require additional processing to insert data points between the collected points using optimized interpolation techniques. Adding the additional data points will ensure the display remains smooth and accurately represents the aircraft flight path.

The processing scheme must also provide some type of error eliminating algorithms to eliminate occasional "spikes" typical in transmitted data streams. These procedures roughly equate to running an aircraft simulator algorithm to serve as a "buffer" between the recorded and displayed data. The data files for each aircraft must also be synchronized to accurately show the relative position of each aircraft during the flight.[12]

Display System Equipment Requirements

When the data is processed and ready for display, the display software should be flexible enough to meet individual unit needs. The user may wish to establish display templates or overlays that depict airspace boundaries, planned routes of flight, or potential threat engagement zones. The system should also allow the user to preselect custom viewing profiles to reduce the time required to set up standardized perspectives. These are all capabilities currently offered on existing ACMI systems, including KITS.

If a host ACMI system is not available, the data can be processed and displayed on conventional PCs. Depending on the level of detail required, these computers require varying levels of performance. For simple renderings of "line art" aircraft, processor speeds of 400 MHz and video subsystems in the sub-1.0 million polygon-per-second range will suffice. Systems in this performance range are commonly used for commercially produced aviation "video games" and will handle basic ACMI display functions.[13]

More advanced display requirements such as realistic geographic representations and three-dimensional aircraft renderings would require more processing power; however, PC-based games already perform these functions on currently available equipment. Today's midrange computer systems provide processing and graphics display capability that exceeds the requirements for existing ACMI systems as well as the initial KITS debrief stations. A Pentium 600 system offers processing power in excess of 1,300 million instructions per second for integer calculations and more than 600 million floating point operations per second. A top of the line video subsystem can handle more than 1.0 million polygons per second. The latest KITS host uses a Pentium III 600 MHz processor and an Emerson and Sutherland video subsystem and outperforms the original Silicon Graphics unit originally specified for KITS in the 1994 production.[14] Smith Industries has also developed a basic ACMI display software program that runs on typical Pentium-class PCs.[15]

The display system must also allow for multiple perspectives, slow and accelerated motion replays, and provide the ability to rotate the scene vertically and horizontally. This capability will allow the user to modify the scene as necessary to present the aircraft maneuvers as desired. The data available also provides all the parameters required to calculate turn rate, turned radius, and additional performance parameters for comparison between aircraft.

An advanced system would allow the user to synchronize AVTR tapes with ACMI-derived scenes. This option would allow the user to display onboard avionics information such as radar and HUD video simultaneously with the ACMI scene. This combination of displays would provide the greatest training benefit for most scenarios; however, it would probably require a special display subsystem that allowed for a single control unit to display both the AVTR and ACMI scenes. For this application, purchasing additional KITS systems may prove to be a less troublesome alternative compared to custom designing a new configuration to simultaneously control AVTR and ACMI displays.

Comparison of KITS and Internal System Features

The preceding analysis demonstrates how internal components can replicate ACMI functionality. Many ACMI features rely only on data readily available on the aircraft 1553 bus. Advanced features would require

modifications; however, these modifications are not extensive and are well within the technical capability of the components. Internal data also offers the potential to greatly expand ACMI functionality beyond what is currently available on any pod-based system. Table 5 compares how an internal system would meet or exceed KITS requirements.

Table 5

Comparison of Internal Systems against KITS Requirements

Requirements Met With Basic System		
Paragraph	**Requirement**	**Internal Solution Method**
3.	Support for the F-15C/D and F-16 C/D 30/40/50	Supports any aircraft with 1553
	Maximum of 24 aircraft	No theoretical limit, limited by host computer processing, memory, and storage capacity
3. a.	Time-space-position information (TSPI)	Aircraft GPS data on 1553
3.a.	Correlate and process weapons events	Postflight weapons processing, FDL modification, or CC modification
3.a.(3)	Weapon simulations	Weapons supported by aircraft computer
3.a.(4) -1	Autonomous data recording	Autonomous operation of 1553 monitor
3.a.(4) -2	Relative position error less than 25 feet	Error specification exceeded using military GPS signal
3.a.(4) -3	Storage for three independent one-hour missions	Recording capacity adjustable based on sample rate and cartridge selection
3.a.(5)	Meeting existing electronic security requirements	No additional electronic emissions
3.a.(5) -1	Recording media easily removed and stored in existing approved security containers	Capability to use existing KITS cartridges or similar units including standard PC-MCIA cards
3.a.(2)	Air-to-air data link, 65 nautical mile range, meeting existing frequency management procedures	Specification exceeded by FDL capability
3.a.(3)	Weapon simulations (real-time kill)	New CC code or FDL modification
3.a.(5)	Meeting existing electronic security requirements	No additional emissions, data-link encryption currently meets security requirements
3.a.(5) -4	Restricted data transmission	Met with FDL specifications
3.a.6	Transportability on aircraft or in specified existing containers	No transportation requirements
3.a.(5) -3	Separation of RED and BLACK data	Records only programmed data
3.a.(5) -2	Unused pods contain no classified data	No pods
3.a.(1)	Meet current weapon interface and loading standards	No weapons interface requirements

Notes

1. These cables are similar to those used to carry television signals across cable TV networks. Most cable TV systems use coaxial wires. Coaxial wires consist of two wires (inner and outer) centered on a common axis that appear like two garden hoses, one inside the other. In cable TV applications, the inner wire carries the signal and the outer wire acts as a shield against external noise. Triaxial wire uses the same principle, with the inner two wires for signal and the outer wire as a shield. For 1553 applications, the two inner wires create a redundant data path for reliability.

2. The data stream "package" can be thought of as a freight train, with each car representing a parameter. The contents of each car are listed in the freight manifest (parameter list with labels). Each avionics component serves as a depot, where data can be on and off-loaded.

3. Jim Davenport, Cubic Systems, telephone interview by author, 17 March 2000, Maxwell AFB, Ala.

4. Michael Golackson, 445th Flight Test Squadron instrumentation engineer, telephone interview by author, 29 March 2000, Maxwell AFB, Ala.

5. Dan McMahon, software engineer, Boeing Company, St. Louis, Mo., telephone interview by author, 29 March 2000, Maxwell AFB, Ala.

6. Golackson interview.

7. Capt Richard Mott, FDL System Program Office, telephone interview by author, 21 March 2000, Maxwell AFB, Ala.

8. Ibid.

9. Dr. Tony Valle, division manager, Sparta Inc., interviewed by author, 9 March 2000, Maxwell AFB, Ala.

10. McMahon interview.

11. Don Simmons, chief engineer, USAF AAC/WRR, interviewed by author, 12 April 2000, Eglin AFB, Fla.

12. Valle interview.

13. Ibid.

14. Bruce Jones, display engineer, Cubic Defense Systems, telephone interview by author, 17 March 2000, Maxwell AFB, Ala.

15. Jim Beaver, software engineer, Smiths Industries, telephone interview by author, 10 April 2000, Maxwell AFB, Ala.

Chapter 5

Potential System Components and Configuration

To test the feasibility of the internal concept, three independent tests were executed to determine if the data available on the 1553 bus was adequate for basic ACMI purposes. In each case, the tests indicated that the data was sufficient for basic ACMI purposes.

Concept Demonstrations

This data was collected on three separate F-15 aircraft with three different recording systems. The data was then provided to independent contractors for processing. These contractors prepared and presented animations of the data that resembled ACMI displays.

1553 Bus Data Processing Example

The data on the 1553 bus is in a binary format. The first step involves converting the binary values into decimal form. This is a standard computer function and results in a data sequence similar to the following (actual 1553 data from an F-15 mission): 23:36:00.046350, 34.9952, –118.2025, 35740.0000, 8330.0000, 4364.0000, 9890.0000, 7432.0000, 7.1741, 44.3353, 1.9531, –1.0313, 1.3828, 5.6360, 5.8173, 84958.7188, –46.7431, 783.5820, 36.5213, 782.8750, –4.6250, 40.6875, 782.7500, –2.6016, 32.9141, 3.4219.

In this maneuver, the aircraft executed a steep dive from 35,000 feet mean sea level (MSL), rolled, and leveled off near 15,000 feet MSL. Because the data follows a known 1553 protocol and sequence, the data can be separated and identified by parameter labels. Parameter labels identify the data by type as each component sends the data to the bus. By separating the data, the individual parameter values are available to the display software for presentation, as illustrated in table 6.

Graphing the altitude parameter highlights the quality of the data available (fig. 11). The recorded data accurately reflects the aircraft performance during the maneuver. The accuracy of the data was verified by a flight-test aircraft tracking radar that independently follows the aircraft flight path.

F-15 SFDR Data Application

The F-15 is equipped with an onboard data recorder intended to collect and store 1553 bus data for use in recreating the aircraft flight path

Table 6

Sample of F-15 1553 Bus Data

	F-15 Parameter Label Time		
	IEGSPL (GPS Latitude)	IEGPLO (GPS Longitude)	IEGPAL (GPS Altitude)
36:00.0	34.9952	−118.2025	35740
36:00.1	34.9952	−118.2025	35740
36:00.1	34.9952	−118.2025	35744
36:00.2	34.9952	−118.2025	35748
36:00.2	34.9952	−118.2025	35748

following an accident. The recorder is known as the Signal Flight Data Recorder (SFDR) and is manufactured by Smiths Industries. This recorder monitors numerous parameters on the 1553 bus and stores the data on a crash-survivable, solid-state memory module. From this data, Smiths Industries successfully demonstrated a flight animation using software they developed to aid investigators in determining the cause of aircraft accidents. The animation was demonstrated on a PC configured as specified in the minimum system requirements. This application shows that data on the bus is useful for ACMI purposes; however, the SFDR is not programmable, and the data cartridge is not accessible without removing panels on the aircraft. The next step was to select the parameters specifically required for an ACMI demonstration.

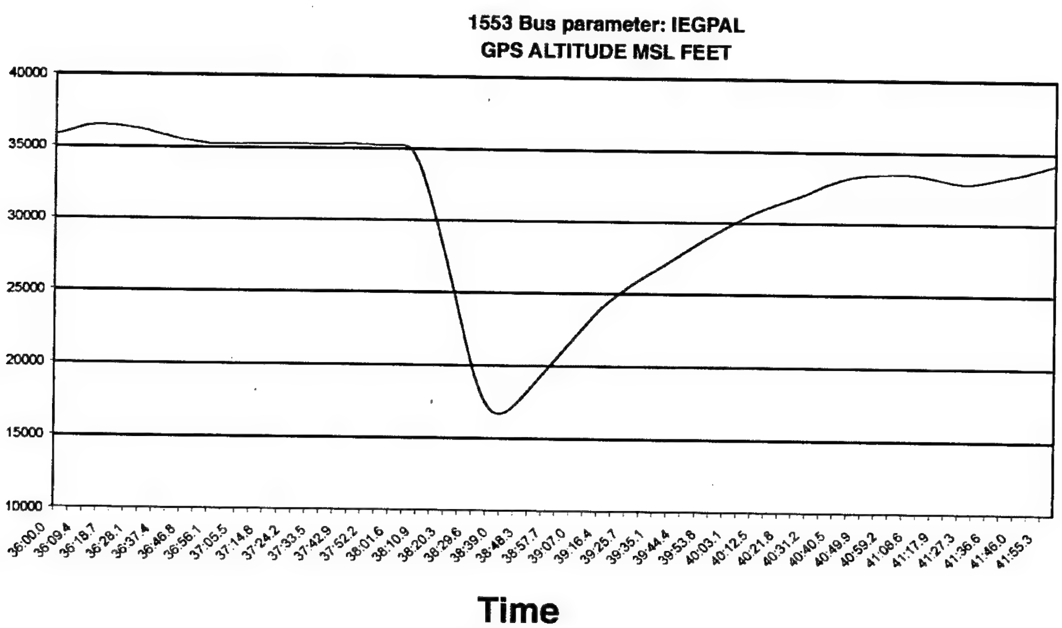


Figure 11. F-15 Altitude Chart from 1553 Data

F-15 Flight Test Data Application

F-15 aircraft at Edwards AFB, California, are equipped with special flight-test recording equipment. This equipment uses the MUXALL technique and records all the data on all the buses for postflight analysis. The data necessary for ACMI animation was extracted from a test-flight data file. This data was provided to a graphics software company known as Sim Author. The company used the data in their flight modeling and simulation software program called Flight Vis. From the data provided, the Flight Vis program successfully animated an aircraft display that recreated the aircraft maneuver (fig. 12). The animation was demonstrated on a PC configured as specified in the minimum system requirements.

This example reinforced the conclusions derived from the SFDR test and demonstrated the concept of selecting specific parameters for ACMI animations. Although promising, this application fell short of providing an example of a data acquisition system that could be installed on all aircraft.

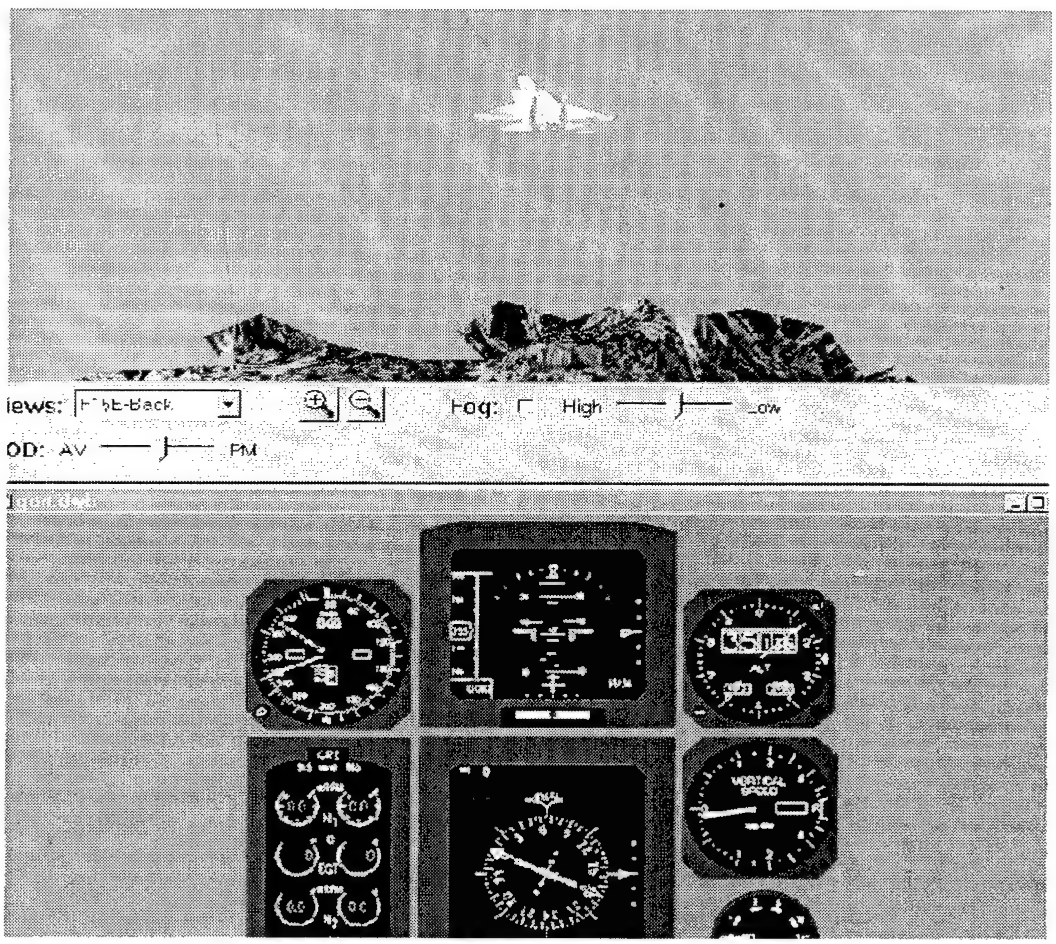


Figure 12. Animation Frame Extracted from Flight Vis Software

The next step was to custom configure a data recorder and install the equipment on the test aircraft.

F-15 Custom Configuration

The final step in this research effort involved building and installing a system that could support fleetwide applications. For this application, flight-test components were used to represent equipment currently available from several manufacturers. The data recording and monitoring equipment was previously installed in the aircraft for GPS integration testing. The installation site, wiring, and connections were chosen using criteria that paralleled those appropriate for an ACMI application.

A data collecting and monitoring system was installed on the F-15, and the demonstration included the components listed in table 7.

Table 7

Potential System Components

Component	Manufacturer	Model	Remarks	Unit Cost (as of 1 May 2000)
Programmable Bus Monitor	Metrics	IFSSR 98172800	Mounted in 47L (Video Tape Recorder Space) Includes 220 million byte (MB) CompactFlash memory cartridge and processor for missile fly-out modeling Requires custom configuration for 1553 Interface Cards	$10,000
Computer System	Dell Computer	XPS R400	Pentium II 400 MHz Processor, 64 MB RAM, 10 GB HDD, STB Velocity 128 AGP video with 16 MB VRAM, Windows 98, Universal Serial Bus (USB) port	$800
Data Port	SanDisk	ImageMate USB	Allows USB connection to read CompactFlash memory cards	$30

The equipment was installed in a small avionics bay behind door 47L (fig. 13). This space was previously occupied by a production aircraft video tape recorder.[1] This installation provides tool-free access for preflight loading and postflight removal of the memory cartridge. Located near the currently installed SFDR, the location also provides access to 1553 bus circuits. A photograph of the installation shows the area available for the recording equipment and highlights the relative size of the installed equipment.

F-15 Parameters for Basic ACMI Functions

Table 8 lists the F-15 parameters that were recorded to display basic ACMI functions. These parameters were recorded at the rate of 4 Hz, resulting in a total recording requirement of 48,000 thousand bytes per minute. At this rate, a 1.0 million byte (MB) cartridge will hold 20 minutes of flight data. This factor can be used to determine the desired storage capability. Currently, cartridges can hold more than 200 MB of data, translating to hours of storage time.

By recording missile and target parameters at launch, missile fly-out routines can be processed by the display system computer. This function would provide basic *post-flight* weapons employment evaluation capability without adding extra hardware on the aircraft, as well as permitting unclassified storage and display of the data files. Unclassified fly-out models are already available from the computer flight simulation game industry, or the system could process the data using real-world models. Hosting the fly-out algorithms on the display system gives the aircrew the opportunity to select classified or unclassified data for debrief.

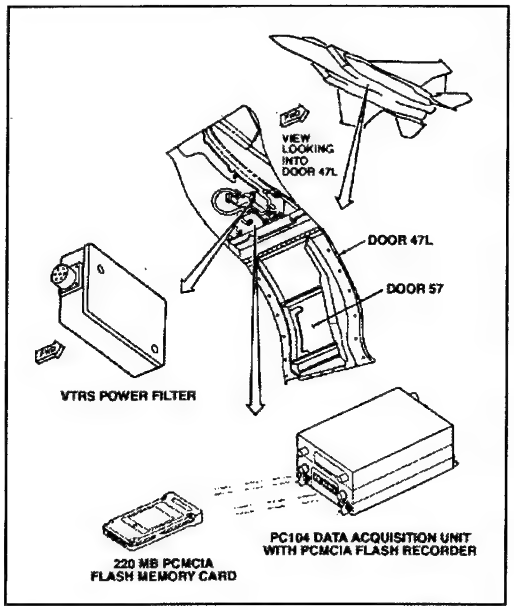
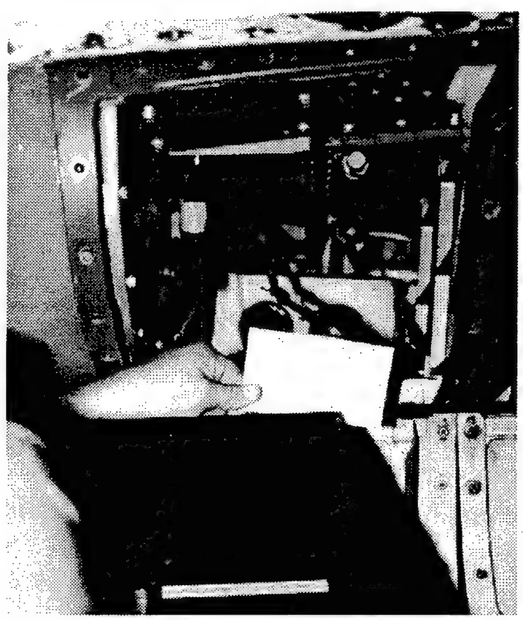


Figure 13. F-15 Data Monitor and Recorder Installation Design

F-15 Custom Configuration Evaluation

The data collected with this hardware was provided to Sim Author. The company again used the data in their flight modeling and simulation software program. From the data provided, the Flight Vis software successfully animated an aircraft display that recreated the aircraft maneuvers. The animation was also demonstrated on a PC configured as specified in the minimum system requirements.

This example reinforced the conclusions derived from the flight-test application and demonstrated the concept of selecting specific parameters for ACMI animations with a programmable 1553 bus monitor recorder. Sim Author also replicated the collected data file to create files representing three aircraft. The Flight Vis program successfully merged the data files for the animation display and provided further evidence that a PC configured with only modest components can display the animations.



F-15 Data Monitor and Recorder Installation

Table 8

Bus Parameters Required for Basic ACMI Functions

TSPI Requirements	**F-15E MIL STD 1553 Avionics Bus #5 Parameters**		
	Label	**Message:Words**	**Bit-Length**
Position			
EGI Latitude	IEGPSL	Msg 9: 5,6	32
EGI Longitude	IEGPLL	Msg 9: 7,8	32
EGI Altitude	IEMSLA	Msg 9: 9	16
Airspeed (CADC)			
True	IPTASP	Msg 1: 1	16
Indicated	IPASPD	Msg 1: 4	16
Mach	IPMNUN	Msg 1: 6	16
AOA	IPOAOA		16
Attitude Components			
INS Pitch	IIPCHL	Msg 4: 4	16
INS Roll	IIROLL	Msg 4: 4	16
INS Pitch Rate (Q)	IIPCHR	Msg 26: 5	16
INS Roll Rate (P)	IIROLR	Msg 26: 4	16
INS Yaw Rate (R)	IIYAWR	Msg 26: 6	16
Heading			
INS True Heading	OTRHDR	Msg 4: 7	16
INS Platform Azimuth	IIPLAD	Msg 4: 2	16
Time			
GPS Time	IEUATT	Msg 8: 1	16
Velocities			
GPS East	IEGVEA	Msg 9: 11,12	32
GPS North	IEGVND	Msg 9: 13,14	32
GPS Up (vertical)	IEGVUP	Msg 9: 15,16	32
INS Velocity X	IIVELX	Msg 4: 5,6	32
INS Velocity Y	IIVELY	Msg 4: 7,8	32
INS Velocity Z	IIVELZ	Msg 4: 9,10	32
			Total bits per cycle: 192
			Bits at 4 Hz = 800 bits per second

Demonstration Evaluation against Success Criteria

To determine if the above demonstrations warrant continued concept development, the results were evaluated against the success criteria. Failing to meet these criteria would indicate that an internal system would have limited potential to meet operational requirements and present a favorable alternative to the current pod-based systems. These criteria were developed for comparison of a basic system and do not necessarily reflect the potential for an internal system to replicate systems used in large force training exercises or capabilities required by the JTCTS. Table 9 lists the results of the evaluation.

As 1553 devices, these components are candidates for inclusion in the concept demonstration. The US Navy and Israeli Air Force (IAF) are also testing internal systems.

The US Navy is testing a PC 104 component added to the F-18 and AV-8B data transfer cartridges. These devices currently transfer data to the aircraft central computer during engine start and record data just prior to engine shutdown. The cartridge receptacle is connected via a 1553 bus. Access to the 1553 bus may allow the modified cartridge to store internal data for ACMI functions.[3]

The IAF is also considering an internal ACMI system. The details on this system were not available (classification issues); however, the existence of the program supports the decision to pursue an internal system. It is highly likely that the factors identified in this study were also recognized by the IAF and convinced their engineers of the advantages an internal system offers. Any concept demonstration study should attempt to ascertain as much as possible about this and any other foreign systems.[4]

Notes

1. The F-15 fleet has since been modified with a tape recorder mounted in the cockpit. This space is now available in all production F-15 aircraft.

2. US Air Force Flight Test Center, *An Investigation of the Squadron Air Combat Training System (HAVE ACME)*, AFFTC-TR-96-23, Edwards AFB, Calif., June 1996.

3. Ron Williams, software engineer, Sim Author, interviewed by author, 11 May 2000, Maxwell AFB, Ala.

4. Todd Kortbein, URITS program director, Metric Corporation, interviewed by author, Maxwell AFB, Ala., 15 March 2000.

Chapter 6

Potential Advantages

New conditions require, for solution—and new weapons require, for maximum application—new and imaginative methods. Wars are never won in the past.

—Douglas MacArthur

Developing and implementing an internal solution offers numerous potential advantages. Internal solutions can provide basic ACMI functionality at a fraction of the cost of existing systems. Internal solutions also offer fleetwide installation potential, greatly enhancing training effectiveness on every mission. Internal systems free the aircraft from relying upon ground-based stations and external pods. This change in ACMI methodology provides improved training availability and combat debrief potential, and it opens the doors to a wealth of data previously unavailable to pod-based systems. Internal components also preserve the natural aerodynamic and radar reflectivity characteristics of the aircraft.

Financial Considerations

Current pod-based solutions are extremely expensive. Operations and maintenance (O&M) costs of existing ACMI facilities range from $6 million to $40 million per year.[1] Purchasing a new installation including 24 pods and two debrief stations can run as high as $15 million.[2] A significant portion of this cost involves the development, production, and maintenance of external pods. US Air Forces in Europe (USAFE) spent more than $3 million in 1999 to lease a system similar to KITS, known as USAFE Rangeless Interim Training System (URITS). This system, including approximately 70 pods and eight debrief stations, is on a lease program with pod and debrief system O&M expenses approaching $5 million per year. Adding 24 more pods would cost more than $1 million, while an additional four debrief stations would cost more than $300,000 per year.

ACT-R pods similar to those used in the KITS system currently cost between $180,000 and $250,000 each. O&M on these pods is typically contracted on an annual basis. The Alpena KITS program currently spends just under $1 million per year on contracted maintenance, while contractor maintenance on the Nellis Air Combat Training System costs $2.5 million per year. The USAFE URITS program could spend up to $7 million in fiscal year 2000 if requested additional pods and debrief stations are approved.[3]

Avionics Component Duplication

Pod-based systems suffer additional cost penalties due to component duplication. ACT-R pods include transmitters, GPS receivers, INUs, air data sensors, encryption devices, and recording systems already installed on modern aircraft. In effect, pod-based systems pose double cost penalties. The user must maintain and purchase two sets of avionics and incur the associated O&M costs of duplicative, unnecessary equipment. Unless the pod components are identical to aircraft components, pod-based systems further increase maintenance manpower and diagnostic and training requirements on unnecessary components. Pod maintenance contracts reduce the military manpower requirements; however, they retain the component duplication cost penalty.

System Development and Testing

Internal systems offer reduced development and testing expenses. Most of the features necessary to enable ACMI functionality can be accomplished with minor software modifications and minimal hardware modifications. Developing ACMI capability on existing components is potentially much less expensive than procuring and testing new components primarily because external components require additional carriage and release testing.

All external components must be specifically tested for carriage throughout the aircraft flight performance envelope. These tests include vibration, flutter, aerodynamic loads, environmental, and emergency jettison testing. These procedures are extremely time-consuming and expensive and must be performed on each aircraft type. ACC spends millions of dollars on external carriage testing. Developing internal components eliminates these expenses.

Accident Liability

External components increase the potential for accident liability expenses. If the pods are procured under a leasing agreement, the user is responsible for costs due to mishandling or damage of pod components. If an external component falls off the aircraft during flight, the user may be subject to extremely expensive liability claims from injured parties on the ground. Falling objects can also damage property and livestock, again exposing the user to liability claims. Loading and maintenance personnel may suffer accidental or repetitive motion injuries during routine operations. Liabilities under these circumstances can range from increased temporary medical costs to permanent disability claims.

Performance Advantages

Developing internal solutions offers several potential performance advantages over pod-based systems. Internal solutions can provide daily

access to ACMI features, greatly increasing training effectiveness and combat performance. Stored data from daily missions is available for review by aircrews who did not participate in the mission. Reviewing additional missions can offer unique training opportunities. Using existing aircraft components can provide unique avionics integration advantages not available on external components. Additionally, software solutions are more easily modified to meet changing requirements. Internal solutions do not alter the aircraft aerodynamic and radar cross-section characteristics and provide training in maintaining combat representative configurations.

Increased Aircrew Performance

Routine availability of ACMI systems will greatly enhance aircrew training regimens. Currently, only 7 percent of US reserved training airspace provides ACMI capability.[4] ACT-R systems will greatly increase this percentage; however, current acquisition funding will not provide fleetwide installation. A recent survey indicates that if ACMI functionality was always available, aircrews would use the system on nearly every mission (see appendix B for survey details). Pod and range availability problems are the top restrictions to daily use, even in locations with dedicated ACMI resources. Routine, daily access to ACMI functionality can also provide unique training opportunities to other aircrews.

Data storage and mission replay capability of ACMI allows aircrews who did not participate in a training mission the opportunity to observe and learn from the experience of their colleagues. The stored data files also provide potentially enlightening segments useful for reinforcing specific lessons during academic or other instructional sessions. This "virtual training" potential can be particularly beneficial for periods of flight inactivity or to allow inexperienced aircrews additional "flight time."

Avionics Systems Integration

Combining the features of internal components as an integrated system proposes several advantages over external systems. Using actual aircraft components reduces the potential for inaccurate performance representations that could lead to negative training values. Monitoring internal systems prevents data delays and potential data losses inherent in providing data to external components. Any data required by the external component that is not available through the connections provided by the mounting hardware must be simulated or "injected" by the pod. Simulated weapons loads and missile capability data not available to the pod must be programmed in the pod separately, increasing mission preparation time.

System Maturation and Development

As the needs for ACMI functionality change, internal solutions may allow software modifications to meet the new requirements. Relying on existing

components also reduces the potential for extraneous avionics to become obsolete. Integrating aircraft avionics through software modifications also reduces potential for hardware conflicts resulting in complex system failures. As additional features are developed, these components can be tested and modified on existing aircraft test platforms using standardized, well-established procedures.

Preservation of Airframe Characteristics

Internal systems do not alter the aerodynamic and radar signature characteristics of the aircraft. Although the additional aerodynamic drag generated by a single external component may not significantly degrade aircraft performance, certain combinations of devices or configurations can degrade handling qualities and increase aerodynamic instability. In out-of-control circumstances, any aerodynamic or weight asymmetry can negatively impact an aircrew's ability to recover the aircraft. External components will also alter the aircraft radar signature.

Increased reliance on reduced radar reflectivity will eventually preclude the use of external components. Even small changes in the aircraft structure can represent dramatic increases and radar cross section. Varying configurations create nonrepresentative training scenarios in the electromagnetic environment. These shortfalls are forcing planners to consider only internal solutions for future aircraft such as the F-22 Stealth and proposed Joint Strike Fighter (JSF).

Maintenance, Logistics, and Manpower Considerations

Podless alternatives offer significant maintenance and manpower advantages over current systems. External pods require routine loading and unloading, as well as special training for maintenance, diagnostics, and repair. These factors increase manpower requirements for daily operations and increase wear on aircraft and pod components.

Loading External Pods

External pods require special "load crew" certification for maintenance personnel. This requirement includes the development and publication of loading procedures and technical manuals, as well as additional component specific training. Current ACT-R pods weigh more than 100 pounds, requiring a two-man load crew for installation. External pods also create unique aircraft configuration control challenges. Maintenance personnel typically prepare aircraft for daily missions up to 24 hours in advance. In an effort to reduce the potential for lost training due to a "ground abort," maintenance personnel also prepare extra or "spare" aircraft. If the aircrew finds the planned aircraft unfit for the mission and must transfer to a spare, the spare aircraft

must also be configured with the external pods. If a spare aircraft is not configured properly, the load crew must then transfer or install the pod on short notice. This procedure potentially increases the risk of personnel injury, dropped pods, or incorrect loading.

Uploading and downloading procedures increase physical wear and damage potential on aircraft and pod components. Every time a pod is installed, the potential exists for unintentional mishandling or damage due to contact with aircraft structure, storage racks, or inadvertent drops to the ground. Loading also subjects components to additional shock and vibration, potentially shortening component life. External pods are physically and electrically connected to the aircraft through standard missile launchers. Multiple uploads and downloads increase the wear on electrical connectors and physical mounting points. Failure of these components can directly degrade aircraft combat capability at the most inopportune times.

Storage and Transportation

External components increase O&M expenses and complexity due to additional storage and transportation requirements. Unless every aircraft is configured with the external pod, the components must be transferred between aircraft as needed. Certain maintenance actions may require removal and reinstallation of the pods. This requirement forces the user to consider storing and transporting pods between aircraft. Unused pods or pods awaiting repair must be stored in a safe location, accounting for environmental and security requirements.

The pods, load crews, and associated support equipment must be deployed with the aircraft during off-station training. Transportation requirements may include special containers and cargo-loading equipment and procedures. If the users elect to deploy with the pods mounted on the aircraft, the components are subjected to unnecessary wear and aircraft fuel costs for the deployment are increased. Any transportation activity also increases the risk of damage to the external components and subjects the pod to additional shock and vibration.

Risk Reduction Potential

Flight operations exist in an environment of multiple risk factors. Any increase in a single risk factor can negatively impact overall operations and risk. External components increase operational and technical risk of flight operations. These devices increase the potential for dropped objects, personnel injury, and unintentional aircraft damage. Electrical failure of external components can damage internal components. Electromagnetic emissions from external components can damage or interfere with internal system operation. Failure to develop internal systems also increases the technical risk of developing future aircraft. The F-22 and proposed JSF will require internal systems. Developing and

testing internal solutions now will reduce technical and fiscal risk of including internal ACMI capability on these aircraft.

Flight Operations Risk

External components increase flight operations risk by increasing the potential for loss, damage, and injury. Any additional aircraft hardware must be inventoried, stored, and accounted for. Components and associated support equipment can be lost or damaged in transportation and storage. Both the aircraft and external components can be damaged during loading and maintenance procedures. Increased maintenance actions also increase the risk of personnel injury. Nonstandard aircraft configurations increase the risk of injury to maintenance personnel during ground operations. Improper loading procedures can increase the risk of objects falling off the aircraft. Extreme operating environments may cause dislodged components to strike aircraft control surfaces and damage aircraft structure.

Electrical Subsystem Risk

External components increase the demands on aircraft electrical systems. Component failure on the external pod can also interfere with or damage internal electrical components. Any additional hardware increases the risk of circuit overload and the potential for electrical fire. Adding extraneous equipment also increases the complexity of electrical circuits, complicating troubleshooting and diagnostic procedures.

Electromagnetic Interference and Emissions

External components increase the potential for electrical and electromagnetic interference. Modern aircraft operate in a highly complex electromagnetic environment, and any additional component requires careful testing to rule out potential interference with existing onboard systems. Additional components may be required to compensate for the changes in the electromagnetic environment created by emissions from nonstandard configurations. Altered data paths and avionics communications circuitry can also interfere with normal system operations. Any new electromagnetic emissions must be reconciled and controlled through standardized frequency management protocols. Any data emanating from external components must be measured and screened for classified information. Additional data-link communications requirements will increase the need for additional encryption schemes and devices. Even encrypted data streams increase operational risk by providing data to adversaries that can eventually be recovered and exploited.

Notes

1. "Rangeless Pilot Training Is Next Up for Air Force," *National Defense*, November 1996, 32.

2. Alex Koenig, Cubic Systems, telephone interview by author, 17 March 2000, Maxwell AFB, Ala.

3. Lt Col John Jannazo, system program director, AAC/WRR, interviewed by author, 12 April 2000, Eglin AFB, Fla.

4. Lt Col Frank DiGiovanni, Headquarters ACC/DR, telephone interview by author, 31 January 2000, Maxwell AFB, Ala.

Chapter 7

Conclusions

It may be said that warfare has acquired a new phase—technological war. In the past, research and development were only preparation for the final and decisive testing of new systems in battle. Today, the kind and quality of the systems which a nation develops can decide the battle in advance and make the final conflict a mere formality—or can bypass conflict altogether.

—Bernard Schriever

No application of technology will replace the need for effective and realistic combat training. As training budgets decline, commanders must develop methods to exploit limited funds fully. Although aircrews have become highly proficient in manual techniques of recreating mission events, these methods are severely limited. The limitations of manual methods are well known and have spawned the development of technological solutions. For more than 25 years, ACMI systems have proven their value and continue to serve as an extremely effective combat training enhancement. Unfortunately, as with many technological solutions, the price has been high. The extremely high cost of developing and maintaining ACMI ranges relegated the systems to occasional use and drove the systems to be reserved for large force training exercises. Despite renowned popularity, the systems have never been adapted for day-to-day, routine training missions. Even the most recent attempts to provide pods for an entire wing of aircraft for daily training have failed. Unless pods are supplied for every aircraft, plus spares, crews will eventually end up with an unconfigured aircraft. The primary limitation preventing fleetwide application is reliance on externally mounted pods.

Recent developments in ACMI technology have removed the requirement for ground-based towers. The latest "rangeless" systems promise ACMI availability in any airspace and on any mission. This is a great step forward; however, the development of the latest systems falls short of the goal of routine accessibility. Still relying on external pods, these new systems retain many of the limitations of the earlier systems. Although the systems may represent the best solution for full-scale, large force employment exercises, investments in these systems have precluded the development of fleetwide capability.

The technical challenges that forced reliance on pod-based ACMI systems have been overcome with modern internal avionics components. Onboard digital microprocessors have replaced legacy analog apparatus. Unreliable, mechanical position and attitude devices have been replaced by laser-driven gyroscopes and solid-state GPS receivers. Individual components communicate across miniature networks with a common language,

under the constant watch of a central computer. These advances provide highly accurate data streams ideal for ACMI purposes. The commercial passenger airline market has taken advantage of these characteristics and developed rudimentary mission replay technology in the form of flight data recorders. Simulator data replay has become a standard practice in airline instruction and training programs. Basic ACMI features can be provided by recording onboard data in a similar fashion.

Although no current combat aircraft is configured for internal monitoring and recording of the parameters necessary to replicate ACMI functionality, these parameters are easily recorded by accessing the aircraft 1553 data bus. The three independent tests in this research strongly support this conclusion. Many developmental test and evaluation aircraft have also demonstrated this capability. The required modifications are very limited. Troublesome and unreliable onboard data recording methods have been replaced with compact, solid-state cartridges capable of storing hours of mission data. Basic ACMI features are available by merely refining the methodologies developed by the test community and the commercial airline market.

Advanced features would require minor modifications of existing hardware; however, these modifications are well within the technical capability of the components. Many features would require only software modifications. Internal data can not only replicate current ACMI functions but expand on the original ACMI concept. Internal data offers a wide range of parameters currently unavailable to the pod-based systems. This family of features represents a vast untapped resource residing within modern aircraft. By ending the reliance on external pods, the dream of providing ACMI debrief capability on every aircraft can become a reality. Informal surveys suggest that aircrews are eager to take advantage of routine ACMI access.

Recent advancements in PC technology and commercial flight simulator software can replace the costly debrief and display systems currently used in the latest ACMI programs. Computation power and graphics manipulation speeds of modern PCs exceed the capabilities of specialized components available when current systems were developed. In the past, only custom-built, highly specialized computer systems were capable of processing the vast amounts of data created during ACMI missions. Today, the video processing power that once required a dedicated computer system can be purchased for less than $200 on a single PC-based expansion card. The speed and power of modern PCs have opened the doors to a commercial simulation market, overtaking what was once a closed military industry. Modern PC-based game software rivals the capabilities that were once only available with multimillion-dollar ACMI systems. Leveraging this current technology can greatly reduce the cost of ACMI display and processing systems and foster fleetwide availability. Commercial game software programs also offer unclassified algorithms that aircrews can use on a daily basis without fear of compromising classified data.

The potential benefits of developing an internal system far outweigh the limited cost of procurement. Beyond potential fiscal savings inherent in eliminating extraneous components, providing routine access to ACMI debrief capability promises greatly improved training effectiveness. Improved training can potentially reduce training requirements and build greater combat effectiveness. Provisions for a combat mission debrief can reduce risk and provide extremely valuable virtual combat experience as well. Internal systems would reduce maintenance and manpower costs, eliminate deployment requirements, and decelerate wear on aircraft structural components. Eliminating external components also reduces numerous risks to aircraft, flight operations, ground maintenance personnel, and civilian populations. Internal components can also provide significant performance advantages over existing systems and offer new features without adding weight, complexity, and altering the aircraft aerodynamic and electromagnetic characteristics. Future aircraft will not support pod-based components. By developing internal solutions today, we can transfer mature systems to tomorrow's aircraft.

The F-22 Stealth fighter and proposed JSF will not accept external components. These aircraft will rely on internal components for ACMI debrief capability. Waiting to develop this capability until these aircraft are in production increases the technical risk of meeting this future requirement. By discovering and overcoming the technical challenges today, these aircraft can enter production without risk of delays due to immature solutions.

Now is the time to fully exploit the avionics capability residing on modern aircraft. Present-day fiscal realities demand that aircrews get the most out of every training mission. An internal system based on currently installed components can meet this requirement. ACMI has proven to be a world-class training enhancement. Making this capability available on every mission, on every aircraft, will only expand the training benefits already demonstrated by ACMI systems.

Chapter 8

Recommendations

Adherence to dogmas has destroyed more armies and cost more battles than anything in war.

—J. F. C. Fuller

When blows are planned, whoever contrives them with the greatest appreciation of the consequences will have a great advantage.

—Frederick the Great

Developing an internal solution is primarily a systems integration and avionics instrumentation effort. All of the components necessary to meet current requirements are available in various forms. The key to success lies in combining the right components with the right software and leveraging capability developed for other purposes. Conventional design and procurement methodologies are not well suited to this development program. A unique, streamlined approach can sift through design choices and produce a low-risk, low-cost alternative capable of refining the proposed concept and demonstrating the feasibility of an internal system.

- Assign concept development activities to the United States Test Pilot School as a student project for the next available training cycle.

This proposal requires a dedicated effort to explore the technical aspects of producing an internal system. An effort of this relatively small magnitude is ideally suited for a student project. The US Air Force Test Pilot School routinely sponsors narrowly defined, low-risk student projects. This institution provides a wealth of test expertise as well as a highly motivated staff dedicated to the success of every project. The students represent a broad scope of experience in numerous platforms and technical career experience. The school also retains the expertise of numerous contractors specializing in computer flight simulation development and aircraft instrumentation.

Located at Edwards AFB, California, the school has access to a wide variety of developmental test aircraft. The test community has extensive avionics integration and aircraft modification expertise. As an acknowledged academic environment, the school is relatively free of the political restrictions that often plague developmental programs. The school also provides funding for limited projects of this magnitude. These factors suggest that assigning concept development to the USAF Test Pilot School offers an expeditious and low-risk alternative.

- Request the 445th Flight Test Squadron to support the USAF Test Pilot School student project and provide design expertise to select and install the appropriate components on instrumented test aircraft.

Choosing the appropriate components and crafting an efficient design is primarily an aircraft instrumentation effort. The 445th Flight Test Squadron located at Edwards AFB retains the services of a highly experienced aircraft instrumentation staff. These engineers have already developed custom avionics bus monitoring and recording devices. The engineering support staff has developed software routines that process and display aircraft 1553 bus data. As a "Combined Test Force," the squadron also employs numerous Boeing Company (formerly McDonnell–Douglas) engineers with access to the full range of technical expertise required to correctly identify and monitor the appropriate parameters. These experts are also well versed in avionics integration issues and will reduce the risk of designing a solution that would interfere with existing systems.

- Assign the Air Force Operational Test and Evaluation Command (AFOTEC) as the concept development sponsor.

A successful demonstration of this system would likely attract support from numerous customers. Several training environments could benefit from the capability offered by this concept. Coordinating and fostering support across various agencies requires sponsorship from an acknowledged operational requirements entity. AFOTEC specializes in promoting these kinds of projects. Located at Edwards AFB, the local AFOTEC detachment is ideally suited to coordinate and support this effort as well as to promote the decision to procure a system for fleetwide application. The AFOTEC staff will also have access to a number of aircrews familiar with past and present ACMI systems. These aircrews will provide a significant pool of expertise that will be extremely valuable in the design and evaluation of the new system. As team participants in this project, the AFOTEC personnel are likely to sponsor a successful demonstration of this concept.

- Include a programmer with experience in and access to commercial flight simulation software on the design team.

Recent advances in PC-based flight simulation software and virtual combat games offer potential starting points for the display and processing components. Industry leaders such as Electronic Arts and MicroProse currently market extremely realistic combat simulation programs. Many of the features required by ACMI systems are already available on these companies' products. By building on existing algorithms, programmers can streamline the software development process and produce usable prototypes much more quickly than an independent, custom approach. These games also offer unclassified performance models that can reduce security requirements on daily training missions. Additionally, these commercially

available products run on existing, widely available hardware. By eliminating the requirement for custom-built systems, the cost of producing processing and display components can be significantly reduced.

- Consider a design including KITS or URITS hardware and minimize the number of specialty components required in the final design.

Most of the components required for monitoring and recording the onboard data already exist. In fact, the components used by the KITS or URITS system may prove adequate. Using proven hardware will reduce technical risk and expedite procurement and development. A common parts base will also streamline the logistics process and provide the larger source for spare parts. Purchasing components already on contract for another system may also reduce cost.

- Include training enhancement demonstrations for a wide variety of missions including air-to-ground and air-to-air missions and show fiscal savings over pod-based systems.

This proposed internal system would provide daily, routine access to ACMI functionality. Currently, ACC tends to view ACMI as primarily a large force employment asset. The proposed system must demonstrate training value for the full spectrum of missions performed by multirole aircraft. By highlighting and demonstrating the capability to greatly enhance all types of daily training missions, the development team can begin to convince ACC leadership of the value of pursuing and funding this initiative. ACC support will likely hinge on financial considerations. By developing a low-cost and low-risk design and highlighting the fleetwide applicability of the system, the difficulty of gaining support can be reduced.

- Include end-users during the concept development and system evaluation phases of the project.

The end-user can be the most efficient and convincing proponent of the system. By including end-users in the development process, the design team can ensure the final product meets daily training requirements. These "advisers" should be selected from across the spectrum of operational and training experience in each weapon system. The aircraft training units are a potentially valuable source of expertise in this area. Acting as consultants, these team members will also provide valuable insight on the potential uses and misuses of the proposed system.

- Create an avionics integration directorate within ACC to foster the development of new avionics implementations and innovations.

This research indicates a lack of emphasis on conceiving methods to fully exploit existing technologies. Many of the avionics component manufacturers do not participate in any kind of integration forums and have

little knowledge of the capabilities of other components in the aircraft. Many of the components in the ACMI pods could have been eliminated years ago had designers more fully appreciated the capabilities available by combining existing components. As new sensors and other avionics components migrate to the next generation of aircraft, the requirement for improved integration will only increase. This kind of integration mind-set has the potential to greatly reduce avionics requirements and offers innovative solutions to the training, combat, and procurement challenges that lie ahead.

These recommendations—concept development, concept design, concept support, leveraging current technologies, minimizing specialized equipment, fostering ACC support, gaining customer support—are not intended to replace completely existing or planned ACMI systems. These alternatives can bring the renowned benefits of basic ACMI functionality to every mission and improve avionics integration infrastructure.

Appendix A

Parameters for Expanded ACMI Capability

Tactical Engagement Data

Radar Mode	TGT Pod Mode	PDT Range	SDT-X Range
Range Scale	TGT Pod Azimuth	PDT Azimuth	SDT-X Azimuth
Sweep Angle	HOTAS Commands	PDT Elevation	SDT-X Elevation
Raster Value	Weapons Load	PTD Rmax	SDT-X Rmax
Tilt Angle	Radar Warning Receiver	PDT Rmin	SDT-X Rmin
Radar Coverage Area	Missile Fly-Out Model	PDT RTR	SDT-X RTR
Time to Intercept	Missile Mode	PDT Close Cue pt	SDT-X Close Cue pt

Aircraft Data

Throttle Position

Stick Force

Flight Control Commands

Chaff Dispense

Flare Dispense

Jamming Program Execution

Fuel Flow

Engine Parameters

Velocities

Appendix B

ACMI Aircrew Survey

Aircraft Type (please circle) **F-16C** **F-16C/G** **F-16C/J** **F-15C** **F-15E**

1. How often do you use ACMI capability?

a. every mission b. $^1/_2$ the missions c. $^1/_4$ the missions

d. < $^1/_4$

2. How often would you use ACMI capability if it was always available?

a. every mission b. $^1/_2$ the missions c. $^1/_4$ the missions

d. < $^1/_4$

3. What prevents you from using ACMI? (please mark any answers that apply)

a. range availability b. pod availability c. debrief equipment complexity d. system reliability e. cost

f. lack of training value added g. too hard to schedule

4. How does ACMI improve your flight debriefs? (please mark any answers that apply)

a. no improvement b. faster debriefs c. more accurate debriefs

d. improved evaluation e. improved weapons employment assessment f. improved maneuver assessment

g. improved recollection of tactical picture h. Other__________

5. Rank order the importance of ACMI functions (1=most important)

a. depiction of aircraft position ___ b. depiction of aircraft maneuvers/formations ___ c. depiction of weapons employment___ d. automated kill notification ___

e. tactical picture___ f. safety of flight monitoring ___

g. missle fly-out profile ___ h. other_____________

6. If basic ACMI functions were available using squadron personal computers, how often would you use this capability?

a. Every mission b. $^1/_2$ the missions c. $^1/_4$ the missions

d. $< ^1/_4$

7. Rank order the missions during which you would find ACMI helpful. (1=most important)

a. BFM b. ACM c. ACT/DACT d. low level

e. air-to-ground weapons delivery f. instrument proficiency

g. instructor training h. other _____________

Survey Highlights

Seymour Johnson AFB, North Carolina

Primary Aircraft: F-15E
Mission: F-15E Initial Training
ACMI availability: None dedicated, limited availability from nearby Multi-Lat System
35 responses

Question #1: 100 percent responded with ACMI use < $^1/_4$ of flown missions.

Question #2: 74 percent responded that they would use ACMI on > $^1/_2$ of flown missions if it was always available.

Question #3: Range and pod availability were the greatest limiting factors, followed closely by debrief system complexity and difficulty of use.

Question #5: 84 percent ranked TSPI-based ACMI capabilities as most important.

3 percent ranked real-time kill notification as most important.

Question#6: 85 percent responded that they would use ACMI on > $^1/_2$ of flown missions if it was PC-based.

RAF Lakenheath, UK

Primary Aircraft: F-15E, F-15C
Mission: F-15E, F-15C Operations
ACMI availability: USAFE Rangeless Interim Training System (20 pods)
33 responses

Question #1: 70 percent responded with ACMI use < $^1/_4$ of flown missions.

Question #2: 94 percent responded that they would use ACMI on > $^1/_2$ of flown missions if it was always available.

Question #3: Pod availability was the greatest limiting factors, followed closely by debrief system complexity/difficulty of use and availability of debrief technicians.

Question #5: 94 percent ranked TSPI-based ACMI capabilities as most important.

3 percent ranked real-time kill notification as most important.

Question#6: 80 percent responded that they would use ACMI on > $^1/_2$ of flown missions if it was PC-based.

Survey Conclusions

Pod-based ACMI is not providing routine access.

Routine access is primarily limited by pod and range availability.

Routine access is highly desired, and if provided, would be used.

TSPI-based ACMI features dominate ACMI utility.

PC-based ACMI would be even more popular than the current setup.